THE MEASUREMENT AND CORRELATION OF SOUND VELOCITY AND TEMPERATURE FLUCTUATIONS NEAR THE SEA SURFACE

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THESIS

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by

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ABSTRACT

The temporal variation of salinity, temperature, water turbulence components, surface wave height, acoustic amplitude and acoustic velocity were studied statistically by computing the auto-correlations and power spectral densities. Correlation times were high for temperature fluctuations with a decay time (e^{-1}) being of the order of forty seconds or greater for temperature and of the order of two seconds for the other parameters. All parameters were shown to exhibit maximum energy at the periods of the predominant surface wave energy.

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TABLE OF SYMBOLS AND ABBREVIATIONS

h_B	Wave Spectra by Baylor Wave Gauge
h_p	Wave Spectra by Pressure Wave Gauge
u,v,w	Turbulence Components
T_1	Temperature as Measured by Thermistor Number One
T_2	Temperature as Measured by Thermistor Number Two
T_3	Temperature as Measured by Thermistor Number Three
T_{BB}	Temperature by Bisset-Berman Instrument
c	Sound Velocity
A	Acoustic Amplitude Modulation
Φ	Acoustic Phase Modulation

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I. INTRODUCTION

This work describes part of a joint experiment by members of the Physics and Oceanography Departments of the Naval Postgraduate School. The Oceanographers basically described the environmental parameters and fluctuations in them while the Physicists simultaneously recorded the affect of the environment on sound projected into it.

A. OBJECTIVES

The major objectives of this work were to describe the oceanic parameters and fluctuations in them as completely as possible while simultaneously recording fluctuations of a sound signal projected into the water.

1. Knowledge of the Environment

Whereas we seek to understand the complex interrelationships of the air and ocean, of particular importance is the affect of the oceanic environment on those devices and energy sources put into it by man for his various purposes. The particular case to be investigated here is the affect of the ocean on sound and the interrelationships of sound and certain environmental parameters near the surface.

a. Oceanographic Environmental Factors Affecting Sound

Traditionally, salinity, temperature, and pressure are the parameters considered as affecting the

velocity of sound in sea water. A more comprehensive knowledge of the environment into which we project sound could show that other factors have a significant role in determining the velocity of sound.

Near the ocean surface the salinity is changed rapidly as evaporation, condensation, and precipitation occur. The affect of the wind on the surface coupled with changes in density cause mixing of the water to occur at varying rates depending on the differences in density in the water column and the velocity of the wind as well as its duration and fetch. This mixing is, however, never so thorough as to cause the water to be homogeneous in the near surface layer.

The temperature of the surface layer can be changed by insolation. The amount of heat added to the water by insolation is dependent upon the time of day, cloud cover and the elevation of the sun. The temperature of the water at the air-water interface is constantly changed by heat transferred between the air and water masses. The direct heat transfer is a function of the difference in temperature that exists between the air and the water. An air mass warmer than the water will transfer heat to the water at the interface and exert a stabilizing influence on the water column. An overlying cold air mass has the opposite affect and tends to cause mixing of the water by convective overturn. Wave action also aids the mixing process but again the water is not usually mixed to the extent that it becomes homogeneous but is found to be in a constant state of flux due to these processes.

It has long been known that in the ocean medium sound pulses propagating over relatively short paths are phase and amplitude modulated due to scattering from inhomogeneities such as the temperature microstructure in the ocean. These thermal inhomogeneities produce random variations in the refractive index of the medium. Thus there is a need for determination of the spatial and temporal variation in the velocity of sound with temperature and in fact with all parameters that affects its propagation.

b. Interrelationship of Spectra

A study of interrelations between spectra of ocean surface heights, water particle velocities, temperature and salinity fluctuations, acoustic amplitude fluctuations, and acoustic phase modulation could give some insight into the affects of inhomogeneities in the environment on sound. Time-series measurements are needed to develop the statistical relationships between wave spectra, underwater turbulence, temperature microstructure, bubble populations, and scattering of acoustic energy from the sea surface. This need was stated in 1960 when LaFond noted the necessity of simultaneously measuring during acoustic tests a number of oceanographic parameters which were believed to influence underwater sound transmission.

2. <u>Scope of the Research as it Applies to Near Surface Problems</u>

a. Data Needed

Data must be acquired to fully describe the environment into which sound is being projected. These will

allow comparison of results in a systematic fashion which could assist in determining specific associations heretofore unnoticed or undocumented.

b. Purpose of Experiment

The purpose of the experiment was to completely describe the small-scale physical properties in the upper ocean and to determine their temporal and spatial interrelationships. The experiment was designed to investigate the complete near-surface physical environment and its interaction with sound waves.

In 1969 Campanella performed an experiment whose objective was to experimentally observe the relationship between the time autocorrelation function of the amplitude of sonic pulses propagated in a random medium and the time autocorrelation function of the temperature microstructure, and hence of the random refractive index of the random medium. His experiment (performed in electrically heated tap water in a small laboratory tank) showed that the time autocorrelation of the sonic-pulse amplitudes was equivalent to that measured for the temperature microstructure.

In realizing the object of determining the relation and affect of the oceanographic parameters on the acoustic parameters there exists a secondary objective to investigate the feasibility of using acoustic devices as sensors of fluctuating oceanographic parameters.

Many spatial and time scales affect sound propagation. However, these studies are oriented towards

achieving an understanding of small scale interactions in the upper ocean. Small means spatial scales of the order of meters to the smallest size able to be resolved by the instrumentation either by size or by the time constant of it. The largest scales will be imposed by the length of the record.

3. Parameters to be Studied

A determination of the specific parameters to be studied was based on instrumentation available and the limitations of the recording equipment. There are several obvious omissions such as bubble populations and distribution and particulate matter but the measurement of these parameters will have to remain unrecorded until more appropriate instruments are available for open ocean studies.

a. What Must Be Measured

The basic parameters which must be measured to define the environment are the following:

(1) Wave height (h)

(2) Turbulence Components (u,v,w)

(3) Temperature Microstructure (T)

(4) Sound Velocity (c)

(5) Salinity (S)

(6) Acoustic Amplitude Modulation (A)

(7) Acoustic Phase Modulation (Φ)

b. Where Measurements Were Taken

The actual experiment was conducted at the Naval Undersea Research and Development Center (NURDC) Oceanographic

platform, one mile off Mission Beach, San Diego, California. The tower has carts mounted on rails on three sides which can traverse over the vertical column from the surface to the ocean floor. Instruments were mounted on the most seaward cart and measurements were made at various depths in the water.

c. When Measurements Were Made

The measurements were taken on the twenty-first and twenty-second of October 1971 with as many parameters being recorded according to equipment limitations.

B. REVIEW OF THE PROBLEM

A complete review of the problem would necessitate coverage of the study of the ocean and sound in the ocean from earliest recorded time to the present day. The intent here is not to be historical but to show the basic content of past efforts and relate where knowledge of the subject stands today.

1. General Review

The study of sound in the ocean was initiated by Leonardo Da Vinci in 1490. He described a method of ship location using a hollow tube with one end placed beneath the surface of the ocean and with the human ear placed at the other end to allow another ship to be heard at great distance.

a. Historical Background

In the year 1827 Colladon and Sturm actually measured the velocity of sound in Lake Geneva. Many other

scientists worked on the study of sound in the ocean and the factors affecting it through the years. It became apparent that the major factor controlling the velocity of sound in water was the temperature of the medium. This fact led LaFond to state in 1962 that the principal oceanographic study to be undertaken in relation to sound velocity was the general temperature structural variation of the ocean with time and space. His pursuit of knowledge along this line led to a great amount of data on internal waves in the ocean.

LaFond's basic reason for studying internal waves was their affect on underwater acoustic transmission. Sound passing through these waves is refracted, depending on the angle of incidence with the thermocline containing the internal waves (and other irregularities) and the vertical temperature gradient.

It has been determined that in the upper few hundred meters of the open ocean the density structure is almost entirely dependent on temperature variations. Measurements over the past few years have indicated that one can no longer regard temperature as a continuous variable with depth. Instead, extremely narrow layers (lenses) of water separated by strong temperature gradients appear to be interleaved.

b. Most Recent Measurements and Findings

An investigation of the most recent measurements and findings on the velocity of sound in the ocean and its relation to oceanic parameters reveals that a great deal of

time and effort has been spent recording sound velocity in various known water types and by curve fitting procedures developing equations to determine c knowing T, S, and P. If one assumes that the speed of sound changes smoothly with temperature and that the sound-speed derivative decreases monotonically as temperature increases, then aside from questions of absolute accuracy, the Greenspan and Tschiegg distilled-water equation is considered internally the most self consistent (Lovett, 1969). The standard deviation is 2.6 centimeters per second over the widest temperature range (specifically zero to one hundred degrees centigrade).

The exact water type being dealt with in the open ocean is rarely known however, and the more that is understood about the affects of oceanic variables the better will be the results of attempts to predict exactly what sound will do when projected into the ocean. The fact that the ocean is far from the nearly homogeneous well mixed fluid that it was thought to be has been amply demonstrated by measurements over the past few years by Stommel and Federov (1967), Woods (1968) and Denner (1967).

Since there exist many formulas for computing the velocity of sound in use today a look at several will be most helpful in a later discussion of the work carried out at the NURDC Oceanographic tower. Wilson's formula (Wilson, 1960) which was arrived at using only laboratory data from actual ocean S.T.P combinations is:

$$c = 1449.30 + 1.5848 \times 10^{-1} P + 1.572 \times 10^{-5} P^2 - 3.46 \times 10^{-12} P^4$$
$$+ 4.587 \times 10^0 T - 5.356 \times 10^{-2} T^2 + 2.604 \times 10^{-4} T^3$$
$$+ 1.19 \times 10^0 (S - 35) + 9.6 \times 10^{-2} (S - 35)^3$$
$$+ 1.354 \times 10^{-5} T^2 P - 7.19 \times 10^{-7} T P^2$$
$$- 1.2 \times 10^{-2} (S - 35) T$$

This is accurate to six significant digits with dimensions of c in meters per second, T in degrees centigrade, S in parts per thousand, and P in kilograms per square centimeter.

Using Kattegat water with a salinity of 27.405 parts per thousand over the temperature range 4.237 degrees centigrade to 25.164 degrees centigrade the least squares fit gave c in meters per second as:

$$c = 1438.815 + 4.69236\ T_{48} - 5.4843 \times 10^{-2}\ T^2_{48} + 2.77 \times 10^{-4}\ T^3_{48}$$

or

$$c = 1438.813 + 4.69477\ T_{68} - 5.4926 \times 10^{-2}\ T^2_{68} + 2.78 \times 10^{-4}\ T^3_{68}$$

with an estimated accuracy of $\pm$ 0.05 meters per second.

The International Practical Temperature Scale of 1968 was adopted by the Comité International des Poids et Mesures at the October 1968 meeting. The new scale replaced IPTS-48 which had been published by the National Bureau of Standards (Metrologia, 1969) as the official measure. NBS calibrations for platinum resistance thermometers. liquid-in-glass thermometers, and thermocouples have generally been based on the new scale since 1969.

Del Grosso's determination (Del Grosso, 1970) utilizing salinities from 31 to 39 parts per thousand and temperatures from zero to thirty degrees centigrade is:

$$c = 1449.0634 + 4.57462\ T_{48} - 5.27147 \times 10^{-2}\ T^2_{48} + 2.46419 \times 10^{-4}\ T^3_{48} + (S - 35)\ (1.34455 - 1.32888 \times 10^{-2}\ T_{48} + 1.0444 \times 10^{-4}\ T^2_{48}).$$

All of the above determinations for c emphasize the dependence of the velocity of sound on the temperature.

The work done by Liebermann in 1951 showed that temperature inhomogeneities possessed surprisingly small linear dimensions in spite of diffusion processes which tend to obliterate them.

Shonting found that the more closely one examines the temperature field in the upper layers of the ocean the more complex it appears. Small scale temperature fluctuations of the order of 0.05 to one degree centigrade occur spatially distributed in the surface layers. These thermal anomalies apparently occur as highly turbulent or eddy-like features a few centimeters or meters in diameter or even as thin stratafied layers a few meters thick extending horizontally many kilometers. He used the term thermal microstructure to define the observations he had made.

2. Specific Review

Seeking information about specific open ocean studies of the affects of temperature on the velocity of sound we must return to the work done by LaFond.

a. San Diego Experiment Background

LaFond realized that the temperature structure influenced the transmission of sound in the sea and this led to his studies of the vertical fluctuations of isotherms with respect to both time and distance. He knew that a knowledge of the magnitude of these fluctuations would help to understand if not solve the problems of sound transmission variations in the ocean environment. After associating the vertical fluctuations of the temperature structure with internal waves, he found that the most significant thermal fluctuations, from the standpoint of equipment response and variability in sound transmission, are the fluctuations caused by short-period internal waves. These may be grouped in the two minute to two hour wave period range and consist of rapid temperature changes with time that are caused largely by the vertical motion of the thermocline.

LaFond found that the correlation of temperature with reference to time decreased at all depths and that in general terms, the correlation is poor in the isothermal layer and significant for levels in the thermocline and below. He related the low correlation in the near surface to fluctuating atmospheric conditions and stated that this results in patchiness of the surface temperatures even though the fluctuations of the atmospheric conditions may be small.

b. What Has Been Measured

For many analytical purposes most of the ocean for most of the year can be taken to consist of three strata. The first stratum is the surface layer consisting of well mixed, nearly isothermal water. The second is the lower more dense water in which the temperature and density vary slowly. Separating these two parts is the seasonal thermocline region in which the vertical temperature gradient is relatively large. The horizontal salinity gradient is slight and isothermal surfaces nearly coincide with isopycnal surfaces here and an obvious method of observation of internal waves is to measure the vertical temperature or salinity structure in the vicinity of the thermocline. LaFond chose to measure the temperature structure.

Pederson reports simultaneous measurements of sound velocity, temperature and pressure along with depth using the self-propelled underwater research vehicle. A definite change in sound velocity was sensed by the sound velocimeter and correlated to a change in temperature of 0.05 degrees centigrade. Apparently no attempt was made to perform statistical analysis of the signals recorded using SPURV.

c. What Is Known About This Site

LaFond (1962) defined internal waves as undulating swells occurring between subsurface water layers of varying density, even though the density change be slight. It is significant to note that vertical oscillations in the

thermal and density structure of the sea are apparently present in all oceans and at all depths. In his measurements of the vertical oscillations of the thermal structure LaFond found that the speed of internal waves was from 0.11 to 0.6 knots with an average value of 0.3 knots. Fifty per cent of the internal waves were found to be higher than 5.6 feet and fifty per cent of all waves longer than two minutes were found to have periods greater than 7.3 minutes. These measurements were made from the same site from which the data for this experiment was taken and gives some indication of the degree of activity at this location. However these measurements were made in the summer when a sharp thermocline existed.

II. EXPERIMENT

The background material previously discussed provides the basis for a discussion of the actual experiment.

A. SITE

The site chosen was the Naval Undersea Research and Development Center Oceanographic Tower in San Diego, California (Figure 1).

1. History

The tower was installed in the summer of 1959 in water 18 meters in mean depth 1.6 kilometers (approximately one mile) off Mission Beach in San Diego, California.

2. Description

The tower is constructed of four tubular steel legs attached to the ocean floor with steel pins sixty-three feet long driven into the sandy bottom. A pipe framework supports a cement deck and an instrument house twenty-three feet above the waterline. There are two catwalks below deck level which are used for handling gear. Several types of instrument handling gear are available including rail mounted carriages fixed to three sides of the tower. Figure two illustrates the tower as originally configured for NURDC studies.

3. Reason For Selecting

The tower was selected for its stability, accessibility, low self-noise level, exposure to the open ocean and

its economy. One of the major advantages of the tower is that it allowed laboratory-like controls in a natural environment. The limitations of the tower are of course inherent in the fact that it is an immobile platform and therefore restricts measurements to relatively shallow water.

B. SENSORS

The sensors used in the experiment were chosen on the basis of availability and reliability. They were mounted so that the mean current flowed into the sensor array and then past the mounting structure.

1. Sound Velocity Sensor

Sound velocity was measured with a Ramsay MK-1 Deep Sea Probe utilizing only the sound velocimeter portion of the probe.

a. Description

Velocimeters, precision instruments for directly measuring the speed of sound in water, evolved from the first successful sing-around prototype developed in 1957 by Greenspan and Tschiegg of the National Bureau of Standards. The Ramsay velocimeter is of the sing-around type consisting of a transducer and transmitter which transmits a pulse of four MHz into a twenty-five centimeter sound path. The pulse is reflected twice to reduce errors due to water motion. After reflection the pulse is picked up on a receiving transducer that is the input for a high-gain pulse-shaping amplifier. The amplifier retriggers the blocking

oscillator, and a repetition frequency results which is higher than the free-running rate. Thus the water path acts as the delay line where the variation in sound velocity through the water changes the delay and hence the "sing-around" frequency. The frequency also depends on the path length and the circuit delays. The configuration of the path length makes it impossible to measure the length to any desired degree of accuracy. Also, because of selective attenuation, the received pulse rises slowly in comparison with the sent pulse and an unknown time delay is introduced during which the received pulse is below the noise level.

Because of this the instrument must be calibrated in a liquid for which the velocity of sound is known accurately, and the liquid must be similar to that in which the instrument will be used. Thus if the instrument is to be used in sea water, it may be calibrated in distilled water in which the sound velocity is known as a function of temperature.

The pulse repetition frequency (PRF) is between 5,600 and 6,400 Hz depending on the velocity of sound. Sound velocity in meters per second can be found by dividing the PRF by four. The PRF controls the output of the sound velocity oscillator. The output of the sound velocity oscillator will be one half the PRF and twice the velocity of sound in meters per second in the Ramsay probe used in this work.

The electronic package of the probe is contained within a stainless-steel pressure-proof housing that can withstand the pressures found at maximum ocean depths.

The characteristics of the unit are: Range-1,400 to 1,600 meters per second; Output Frequency - 2,800 to 3,200 Hz; calibration accuracy - 0.01 meters per second; response time - 160 microseconds.

The signal from the probe was transmitted via the sea cable to the deck unit. The Ramsay Deep-Sea Probe Control Unit, Model 1B, amplifies the data signal, demultiplexes the f-m telemetry tone signals and converts these tone signals to variable D.C. voltages. Frequency-to-DC converters provide zero to ten volts D.C. over the frequency spans of the channel bandwidths (2,800 Hz to 3,200 Hz for the velocimeter). A block diagram of the velocimeter system is shown in Figure 3.

The signal was then filtered with a Khronhite Ultra-low Frequency Band Pass filter model 330-A set on high input amplitude with a low cut-off frequency of 0.02 Hz and a high cut-off frequency of 2,000 Hz. The signal was then amplified with a Hewlitt-Packard amplifier model HP 2470 before it was recorded.

b. Employment

The velocimeter probe was mounted in the vertical center of the instrument array behind the transducer used for amplitude and phase modulation studies. This placement allowed measurements of sound velocity in close proximity to the other instruments without interfering in their operation.

2. Temperature

Temperature was measured using a specially constructed Wheatstone bridge circuit utilizing a temperature sensitive thermistor as one leg of the circuit. A total of three such circuits were used.

a. Description

Thermistor beads are small glass-encapsulated high-thermal-resistant materials with connecting leads. The resistance of the beads is greatly influenced by temperature (hence thermal resistor). The temperature changes the bead resistance which changes the output voltage of the bridge.

The thermistors were used as one leg of a Wheatstone bridge circuit. These circuits were so constructed that a null could be set for any resistance value of the thermistor and therefore for any desired temperature. The circuit used and its relation to the amplifier and recorder is illustrated in Figure 4.

The temperature sensor used was a type K496 isocurve thermistor manufactured by Fenwall Electronics, Inc., Farmington, Massachusetts. It is a double-bead type which incorporates a special aging process, giving stable and repeatable accuracies not usually obtained with ordinary thermistors. These thermistors were taken from expendable bathythermographs. Statistically, if there is a drift in the characteristics of one bead, the other bead may not change or may shift in the opposite direction. This tends to minimize any overall calibration change.

The sensor is epoxy-potted within a stainless steel tube three millimeters in diameter. The beads are coated with an extremely thin layer of glass which provides good electrical insulation, stops microscopic leakage of gas caused by slight chemical strain release in the semi-conductor caused by hydrostatic pressure, and most importantly permits a thermal response time in sea water of less than 100 milliseconds.

These thermistors are capable of operating over the range from -5 to 30 degrees centigrade making them suitable for ocean temperature measurements. The thermistor's relatively large resistance change per degree of temperature provides a high resolution factor. It has a resistance of about 15,000 ohms at 25.0 degrees centigrade and exhibits a nominal resistance change of about 570 ohms for a one-degree centigrade change at 25 degrees centigrade as compared to less than two ohms for a typical 200-ohm platinum resistance sensor.

The high resistance of a thermistor coupled with its high sensitivity makes it appropriate for use at the end of a conducting cable. Changes in the resistance of the cable due to ambient temperature variations can be neglected for short cable lengths up to about 1,000 meters, since the resistance of the cable is small compared to the resistance of the thermistor. By maintaining a constant current the voltage across the thermistor is a direct function of the temperature therefore requiring no reference or cold

junctions and high amplifier gain is not required which reduces errors due to high gain instability.

b. Construction

Construction of the associated bridges was accomplished with the assistance of Dana Maberry, a technician from the Oceanography Department.

(1) Choosing Components. Thermistors were chosen because of their high sensitivity, fast time-response, minimal effects from lead resistance and low cost. Their low cost allowed several temperature sensors to be used simultaneously.

(2) Assembly. Assembly of the thermistor devices was accomplished using a separate bridge box for each of three thermistors with three additional thermistors prepared in advance in case of breakage of the delicate beads.

(3) Calibration. Calibration was done in a stirred Dewar flask of water using a quartz thermometer standard. The temperature was varied from ten degrees centigrade to eighteen degrees centigrade in approximately one-half degree increments. The circuits were nulled using a single decade box and the nulling resistance was plotted versus temperature. As the temperature increased the resistance of the circuit decreased. The slope of the line for this range was 910 ohms per degree centigrade. Figures five and six give typical calibration curves obtained for the thermistor circuits.

The calibration procedure was repeated with the circuit nulled at ten degrees centigrade and the voltage ouput recorded. The plot showed that as the temperature increased the voltage increased and the bridge proved to be very linear showing an increase of 0.0553 volts per degree centigrade. By use of the single decade box the circuits could be nulled at any desired temperature allowing fluctuations about this "baseline" temperature to be monitored.

c. Employment

The arrangement of instruments was chosen to provide for optimum coverage of the volume of water containing all instruments without causing mutual interference. The sensors were mounted as shown in Figures seven, eight and nine.

3. <u>Remaining Sensors</u>

The sensors described above are those which were the responsibility of the author. The following is a brief description of the other sensors used in the experiment.

a. Baylor Wave Gauge and Pressure Wave Sensor

The surface waves (h) were measured using a surface penetrating resistance wave gauge manufactured by the Baylor Company and also with a pressure wave sensor made by Interstate Electronics.

b. Turbulence Meter

The turbulence measurements (u, v and w) were made using an electromagnetic flow meter manufactured by Engineering Physics Company. This instrument is capable of

measuring two orthogonal components simultaneously. The resolution of this instrument is limited by the wave number scale because of the volume over which the flow velocity is integrated. This limits this particular model to measurements of turbulence with wave lengths greater than about twenty centimeters. Using Taylor's hypothesis this limits the frequency resolution to about one Hertz.

c. Salinometer

A Bissett-Berman inductance salinometer was used to obtain the temporal variation of Salinity (S).

d. Sound Device

The amplitude (A) and phase modulation (Φ) of a continuous sound wave of 20-80 KHz was measured using a source and hydrophone separated by approximately two meters (reference Theses of LCDR Smith and LCDR Routmann).

C. DATA COLLECTION

1. Recorder Used

All data were recorded on a fourteen channel Sangamo model 3500 magnetic tape recorder using FM electronics. Data recording was at 1-7/8 inches per second. The length of each run was approximately twenty minutes.

2. Dates of Collection

The data recording was done on 21-22 October, 1971. Table I is a tabulation of data collected with a check indicating data and a zero indicating non-collection.

3. Auxiliary Data Assembled

As additional data the standard oceanographic observations as delineated in H.O. publication 607 were made. An attempt was made to observe sea life near the instrument array but during the hours of darkness and when the array was deeper than a few meters such attempts were generally inconclusive.

III. ANALYSIS OF DATA

The analog data recorded on magnetic tape consisted of runs of approximately twenty minutes duration. The data reduction required transfer of this information to strip charts which were then used for digitization and statistical analysis. The strip charts themselves were useful in visual correlation work with the records.

A. DIGITIZATION

The digitization procedures were accomplished in three steps as outlined here.

1. Strip Chart Production

The tape recorded data was collected at a tape speed of 1-7/8 inches per second. The tapes were replayed at 7-1/2 inches per second (or 4x speed up) and the information recorded using a Brush Mark 200 eight channel strip-chart recorder. The increased playback speed reduced the twenty minute records to five minutes in length. A speed of five millimeters per second was used on the Brush recorder producing a record 1.5 meter in length. These records were used for visual correlation studies and were also the basis for production of a digitized record for statistical analysis.

2. Digitized Magnetic Tape Production

The strip chart records were taken to the Fleet Numerical Weather Central facility at Point Pinos, California

where a digitized magnetic tape was produced utilizing the Calma Company model 480 digitizer. The digitizer recorded each one-hundredth of an inch variation of the trace from the starting point of each run which was marked by a vertical line imposed on the chart at the start of each recording.

3. Data Card Production

The nine track magnetic tape obtained from the Calma digitizer was converted to data cards using the CDC 5000 Computer at Fleet Numerical Weather Central. These cards were then used as the input data for the statistical analysis done on the Naval Postgraduate School's IBM 360-67 Computer.

B. COMPUTER PROGRAMS

The programs utilized to analyze the digitized data were from the W. R. Church Computer Center library and the files of Fleet Numerical Weather Center's computer center.

1. MISR Program

The subroutine MISR from the W. R. Church Computer Center library was used to compute the mean, standard deviation, skewness and kurtosis for each of the data sets. This was done to serve as a comparison with the values obtained from the second program used in the analysis.

2. FNWC Spectral Analysis Program

This program was the basis for the analysis of data for this experiment. The time increment in this program was 0.2032 seconds per sample which was arrived at by considering the speeds of the recorders and the incremental distance

inherent in the digitization process. This set the Nyquist frequency at 2.46 HZ for all the data analyzed. The two products of interest from this program were the normalized autocorrelation and power spectrum graphs from the CALCOMP plotter.

a. Normalized Autocorrelation Graphs

The Normalized Autocorrelations for each data set were plotted with an abcissa scaled in seconds to a maximum time lag of forty seconds. These plots allowed a quick evaluation of the persistence exhibited by each parameter. Generally the temperature data showed a high degree of coherence while all other parameters showed a much lower coherence. The graphs are shown as Figures 10 to 28.

b. Power Spectral Density Graphs

The power spectra were plotted for each data set to show the contributions of oscillations with various frequencies to the variance of each time series recorded in the experiment. From the graphs shown as Figures 29 to 47 it is noted that though the maximum energy is contributed by periods longer than one-half Hertz the total energy contributed by periods less than this is by no means negligible.

IV. CONCLUSIONS

A. STRIP-CHART COMPARISONS

A visual investigation of the records obtained from the Brush recorder showed an apparently high degree of correlation between the salinity, wave profile, turbulence profiles, sound velocity and amplitude profiles. The periodicity of all of these parameters was about that of the surface waves which were recorded at the same times. The signals from the thermistors did not appear to correlate. A possible reason for this observed behavior of the thermistor signals is that the time constant of the thermistor beads used as sensors was much smaller than that of the other instruments.

1. Run Three

A detailed investigation of the records for this run revealed that the salinity trace and wave height were almost identical records. These records showed no long term fluctuations with the signals showing short period fluctuations about an average value. This base value for salinity was about 33.5 parts per thousand from the Bissett-Berman salinometer and 33.512 parts per thousand from analysis of a water sample taken at the time of the run. This extremely strong correlation between salinity and wave profile at shallow depths held throughout the experiment. There exists a strong possibility that the instrument is somewhat velocity dependent. The vertical orientation of the axis of the

cores of the inductance coils (used as the sensors) could have caused the water contained in the core to move only with the vertical component of the turbulent velocity caused by wave action. This velocity may have been recorded rather than actual salinity fluctuations. This suspicion is substantiated by the similarities between the vertical component of velocity measured with the turbulence meter and the salinity and wave records as well as by the fact that the correlation decreased as the depth at which the recordings were taken increased.

The temperature records showed a long term positive increase throughout this run and the fluctuations appeared to be about the same level throughout the run. The phase amplitude signal fluctuated when the temperature increased. This relation held for all the runs analyzed. There is some indication that the phase amplitude fluctuations decreased if the temperature remained constant in D.C. level, even though short term fluctuations continued.

The vertical component of turbulence and the phase amplitude appeared strongly correlated in frequency, phase and amplitude at times but this correlation did not hold throughout the run.

The long term changes in the temperature records indicates that there was a net movement of water past the sensors. The sound amplitude fluctuations which increased when there was a temperature change support this idea.

2. Run Four

The salinity and wave records for this run show very little correlation. Since this particular run was made near the bottom and wave action here was minimal, this observation supports the conclusion that the salinometer is velocity dependent.

The apparent dependence of phase amplitude fluctuations on temperature changes is again evident in this data. As the temperature showed long term changes the fluctuations in the phase amplitude increased. There also appeared to be correlation between the temperature and salinity signals for this run. The signal from the sound velocimeter also exhibited fluctuations at the same times as those in the temperature record.

3. Run Five

The correlation between the salinity and surface wave signals is high for this run. These data were made at a shallow depth as was run three, therefore supporting the idea that the salinometer is velocity dependent.

The relation between the fluctuations in phase amplitude and an increase in temperature are very evident once again in this record.

The conclusions, or ideas, based on the visual observations of chart records is of course somewhat subjective and must be considered tentative at best. However they point out features that are important enough to warrant detailed examination in future experiments.

B. AUTO-CORRELATION GRAPH COMPARISONS

The most obvious fact obtained from a study of the auto-correlation graphs is the long correlation time exhibited by the temperature signals. Table IV lists the times for the signals to decay to a value of e^{-1}. The temperature signals show long correlation times of the order of forty seconds or greater while all other parameters have decay times of the order of two seconds. The single exception is the graph for thermistor two during run five. The lead for this thermistor parted during the run and was replaced by the spare lead for the last half of the run. This latter portion of the record was analyzed since it was the longer of the two records available. This proved to be a poor choice for there was intermittent contact to the circuit and therefore the record is quite erratic. The consistency of the remaining records leads to the conclusion that the water was well mixed with respect to temperature for all runs.

Generally an autocorrelogram shows fluctuations with the same kinds of periods as the original time series. The fluctuations have been put in phase so that they reach a maximum at zero lag. Using the criterion that the spectrum of the time series probably has a general maximum near the first "peak" observed on the curve the following times are noted for the various parameters and runs as the general maximums. (For a complete listing of all peaks noted see Table II).

1. Run Three

This run shows close agreement among the sound amplitude and thermistor one and thermistor two signals actually analyzed. The approximate time of the first peak of eleven seconds is valid for A and T_1 whereas T_2 is slightly lower at about ten seconds.

2. Run Four

There does not appear to be as close an agreement here as in run three. The first peak observed for A is at twenty-six seconds which is the same as the second period for T_2 with the first at nine seconds. The salinity peak occurs at about 13.5 seconds while sound velocity exhibits a peak at 11.75 seconds.

3. Run Five

This is the most complete run available for analysis and shows the most coherence among signals. The first peak ranges from 7.61 seconds for the wave height to 7.08 seconds for the w component of turbulence. This close agreement of times is carried out through all five peaks plotted on the graphs.

4. Run Six

Although this run contains a different set of parameters than run three it too exhibits the scatter shown in run four.

The conclusion drawn from this view of the analyzed data is that all parameters measured have the same general maximum periodicity in the near surface environment.

C. POWER SPECTRUM COMPARISONS

The use of the power spectra to show where most of the energy of the variance of the various parameters is produced agrees closely with the information derived from the auto-correlation graphs. The information is found in Table III.

TABLE I

PARAMETERS MEASURED ON 21-22 OCTOBER 1971

Run	Time	Depth	h_B	h_P	u	v	w	A	Φ	$\Delta\Phi$	S	c	T_1	T_2	T_3	T_{BB}
1	1419-1439	4.3 m	X	X	X	X	0	X	X	0	X	0	0	0	X	X
2	1530-1550	4.2 m	X	X	X	0	X	X	X	0	X	X	0	0	X	X
3	1616-1636	9.0 m	X	X	X	0	X	X	X	0	X	X	X	X	X	X
4	1648-1708	13.9 m	X	X	X	0	X	X	X	0	X	X	X	X	X	X
5	1728-1748	6.9 m	X	X	X	0	X	X	X	0	X	X	X	X	X	X
6	0354-0448	4.3 m	X	X	0	0	0	0	0	X	X	0	X	0	X	X
7	0546-0622	4.3 m	X	X	X	0	X	0	0	X	X	0	X	0	0	X
8	0650-0715	9.5 m	X	X	X	0	X	0	0	X	X	X	X	0	0	X
9	0725-0749	14.6 m	X	X	X	0	X	0	0	0	X	X	X	0	0	X
10	0802-0821	7.8 m	X	X	X	0	X	0	0	X	X	X	X	0	0	X
11	0832-0852	8.2 m	X	X	X	0	X	0	0	0	X	X	X	0	0	X
12	0929-0945	5.7 m	X	X	X	0	X	X	0	0	X	X	X	0	0	X

TABLE II

AUTO-CORRELATION PEAKS

(All times in seconds)

RUN THREE

A	11.25	18.35	25.84	34.60		
T_1	11*					
T_2	10*	20*	31*			
S	12.49	18.95				

RUN FOUR

A	None	26.24	31.27			
T_2	9	26	36			
s	None	13.54	23.96	34.80		
c	11.75	22.40	33.65			

RUN FIVE

T_1	None evident					
A	7.50	12.50	19.60	27.10	33.35	
T_2	7.19	12.08	19.59	23.13	30.31	38.75
s	7*	13.34	21.46	27.08	34.39	
u	7.29	12.92	21.67	None	33.13	
w	7.08	13.34	21.35	27.08	33.75	
h_B	7.61	13.23	21.65	26.98	33.34	
c	7*	13*	20.83	27.29	32.50	

RUN SIX

T_1	13.34	25.41	37.08			
c	11.25	19.15	35.00			
S	16.08	29.49				

*Indicates peak not definite.

TABLE III

POWER SPECTRUM PEAKS

RUN THREE

T_1 peaks at 0.042 HZ = 23.8 Sec. Period

S peaks at 0.042 HZ

A peaks at 0.020 HZ = 50 Sec. Period

RUN FOUR

T_2 peaks at 0.062 HZ = 16.1 Sec Period

c peaks at 0.073 HZ = 13.7 Sec Period

S peaks at 0.083 HZ = 12.0 Sec Period

RUN FIVE

T_2 peaks at 0.145 HZ = 6.9 Sec Period

T_1 exhibits no peak

S peaks at 0.125 HZ = 8 Sec Period

h_B peaks at 0.125 HZ

v peaks at 0.125 HZ

w peaks at 0.125 HZ

C peaks at 0.125 HZ

A peaks at 0.125 HZ

RUN SIX

T_1 peaks at 0.062 HZ

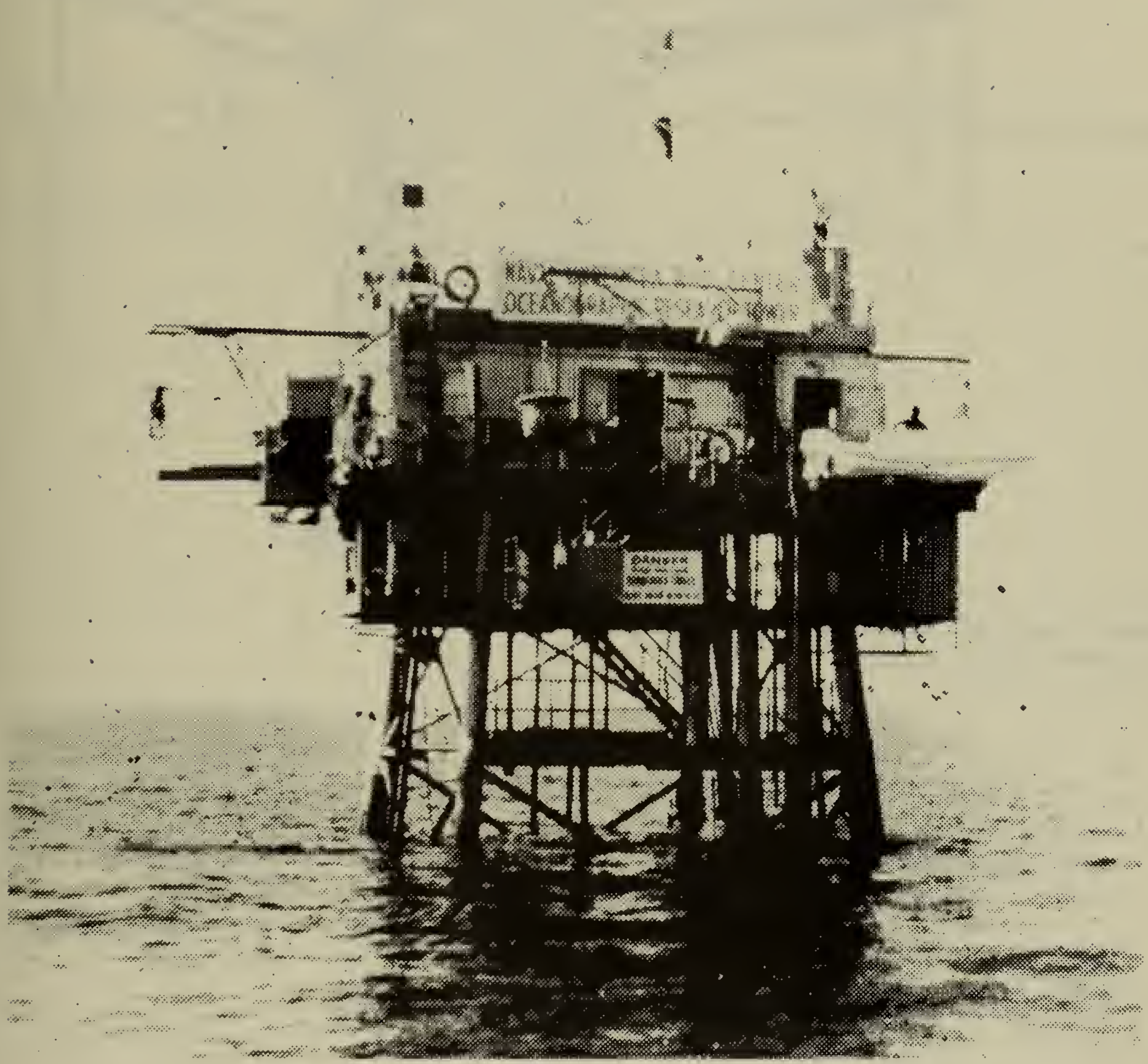
S peaks at 0.047 HZ = 21.3 Sec Period

c peaks at 0.088 HZ = 11.4 Sec Period

TABLE IV

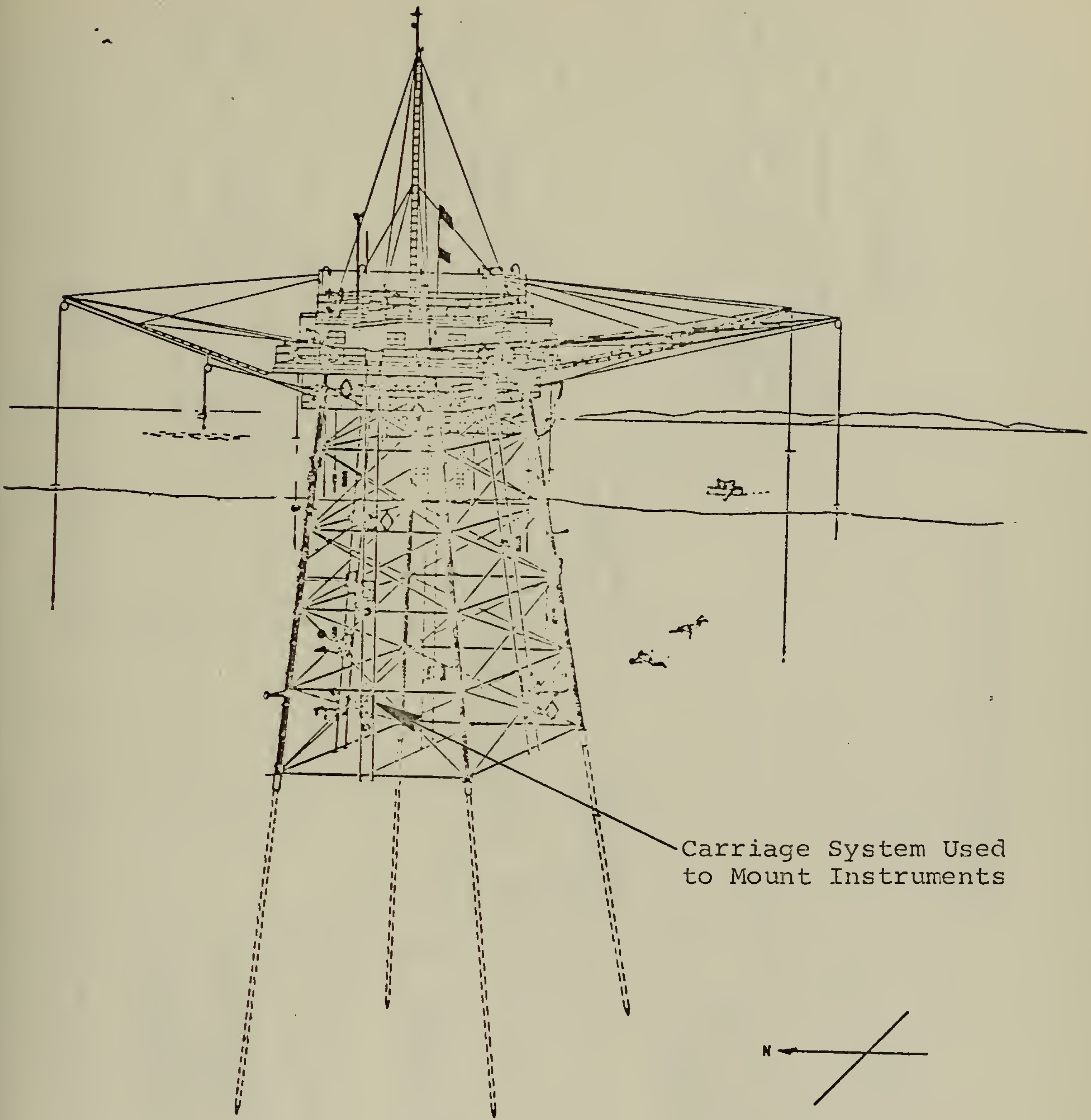
CORRELATION DECAY TIMES

Parameter	Run	Time to e^{-1} Correlation (sec)
A	3	2.5
T_1	3	>40
T_2	3	>40
S	3	1.6
A	4	11.2
T_2	4	>40
S	4	2.6
c	4	1.9
A	5	1.2
T_1	5	38.4
T_2	5	16.6
S	5	1.4
u	5	1.6
w	5	1.2
h_B	5	1.2
c	5	14.7
T_1	6	>40
c	6	2.2
S	6	3.9



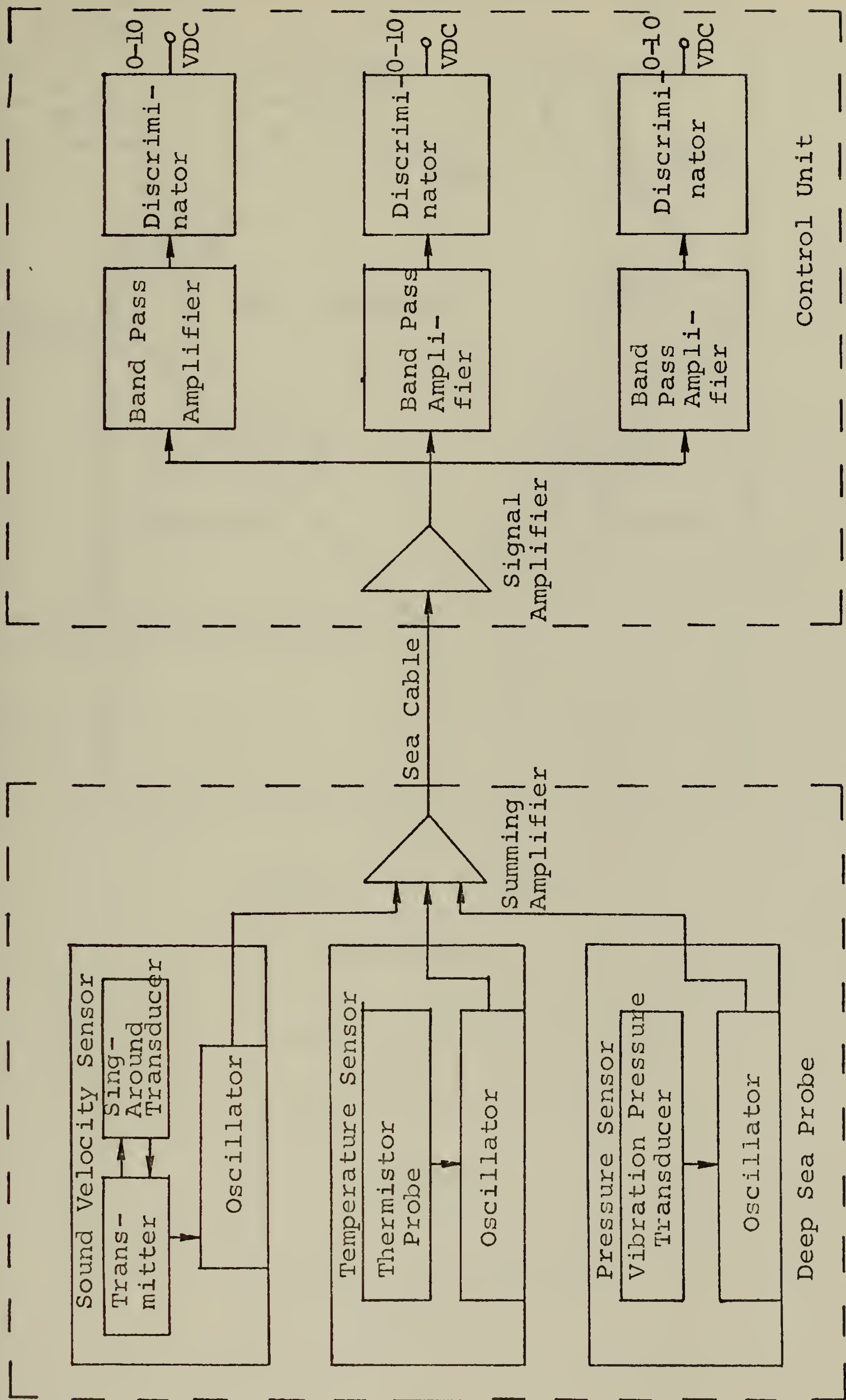
Navy Undersea Research and Development Center
Oceanographic Research Tower

Figure 1.



Research Tower Schematic

Figure 2.



Velocimeter Block Diagram

Figure 3.

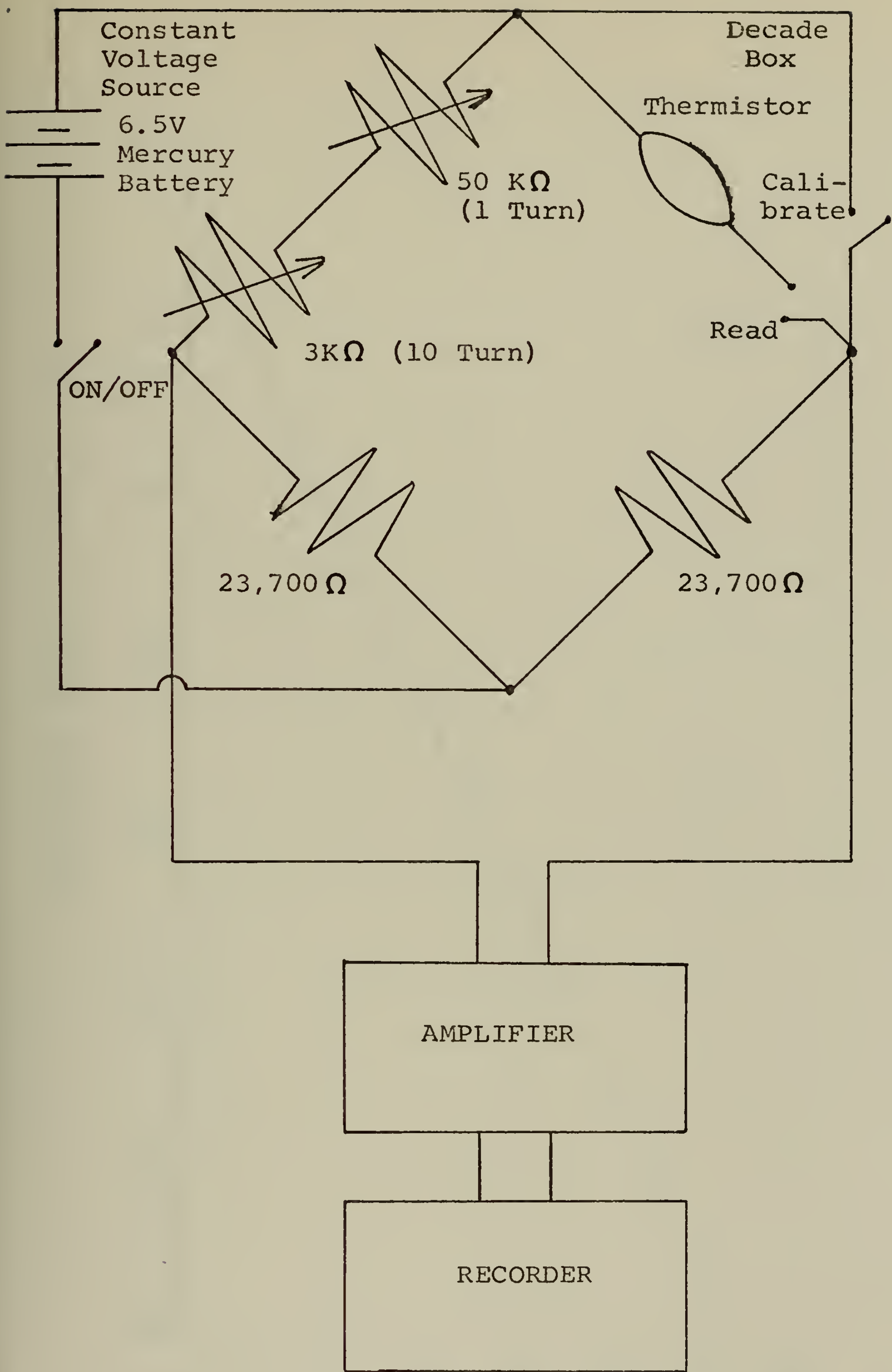
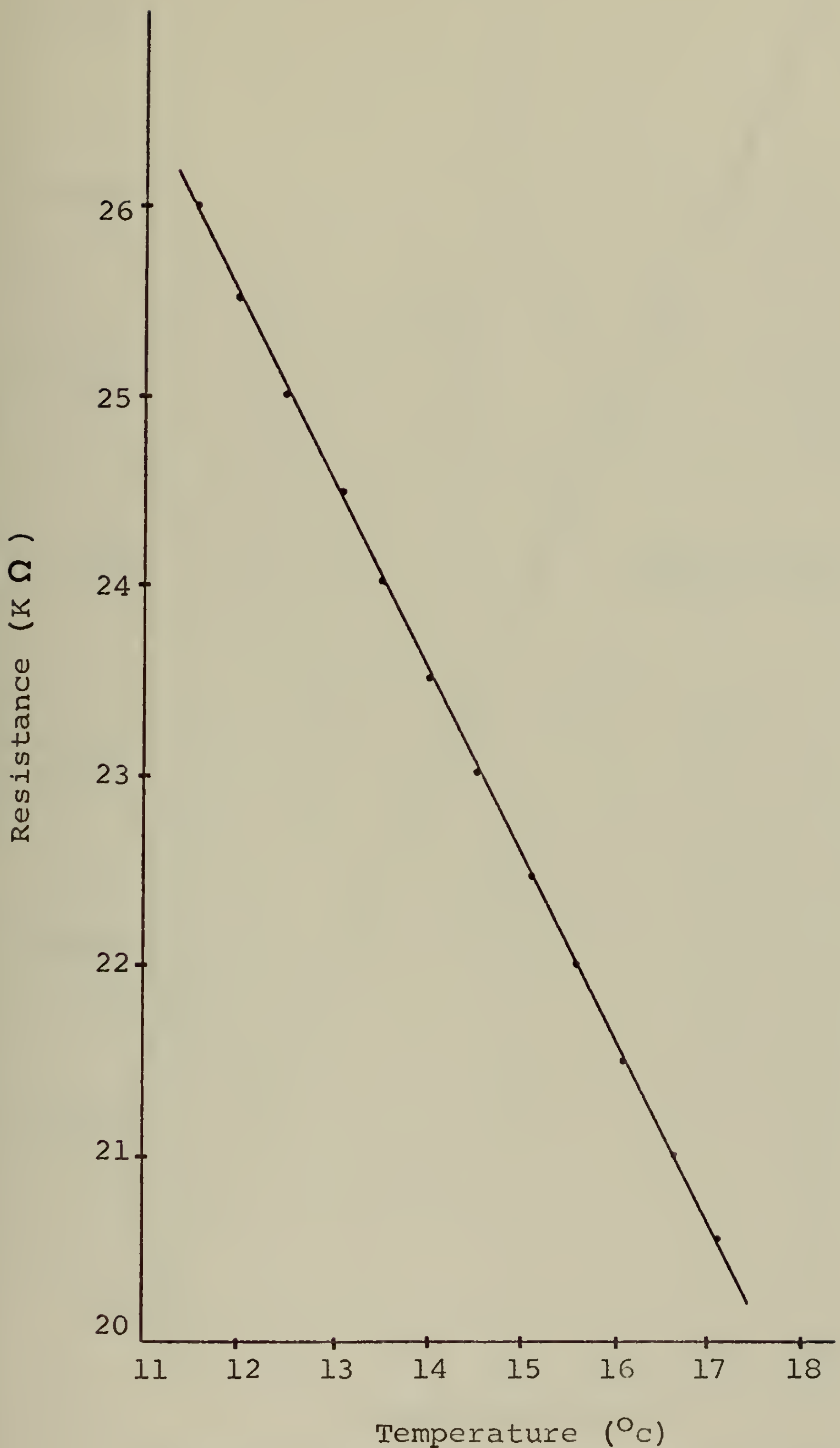
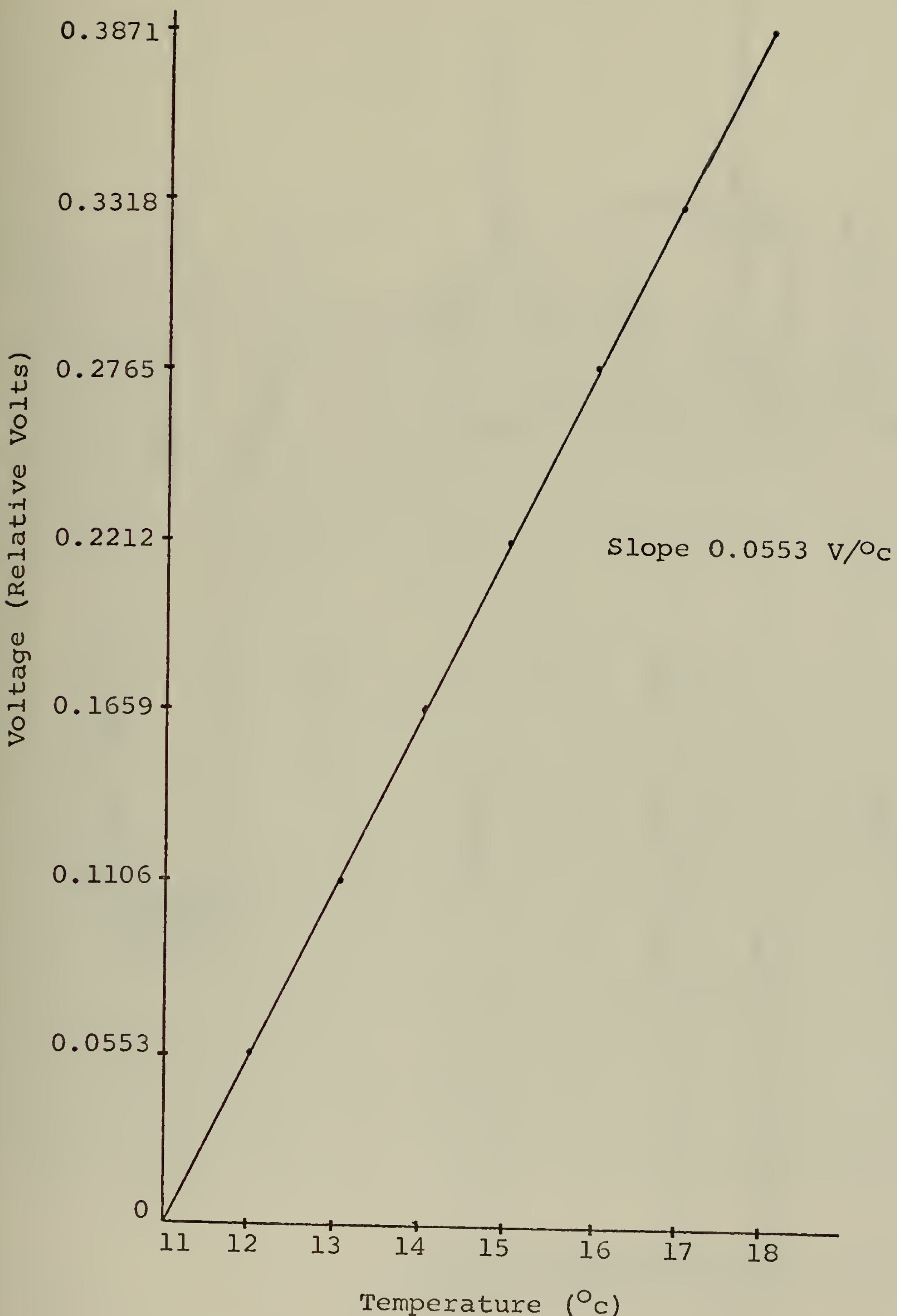

Constant
Voltage
Source
6.5V
Mercury
Battery
50 KΩ
(1 Turn)
Decade
Box
Thermistor
Cali-
brate
3KΩ (10 Turn)
Read
ON/OFF
23,700Ω
23,700Ω
AMPLIFIER
RECORDER

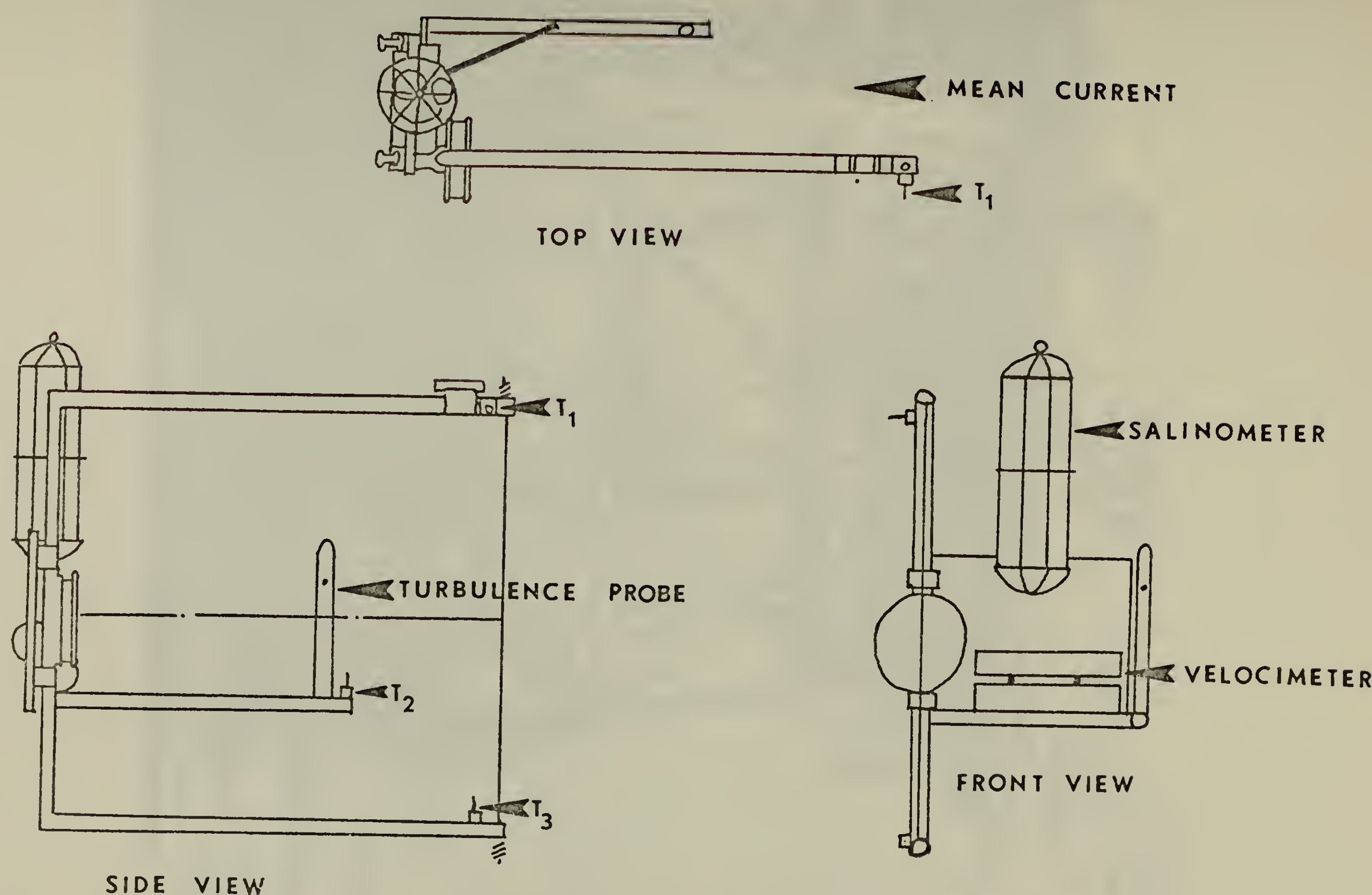
Figure 4.



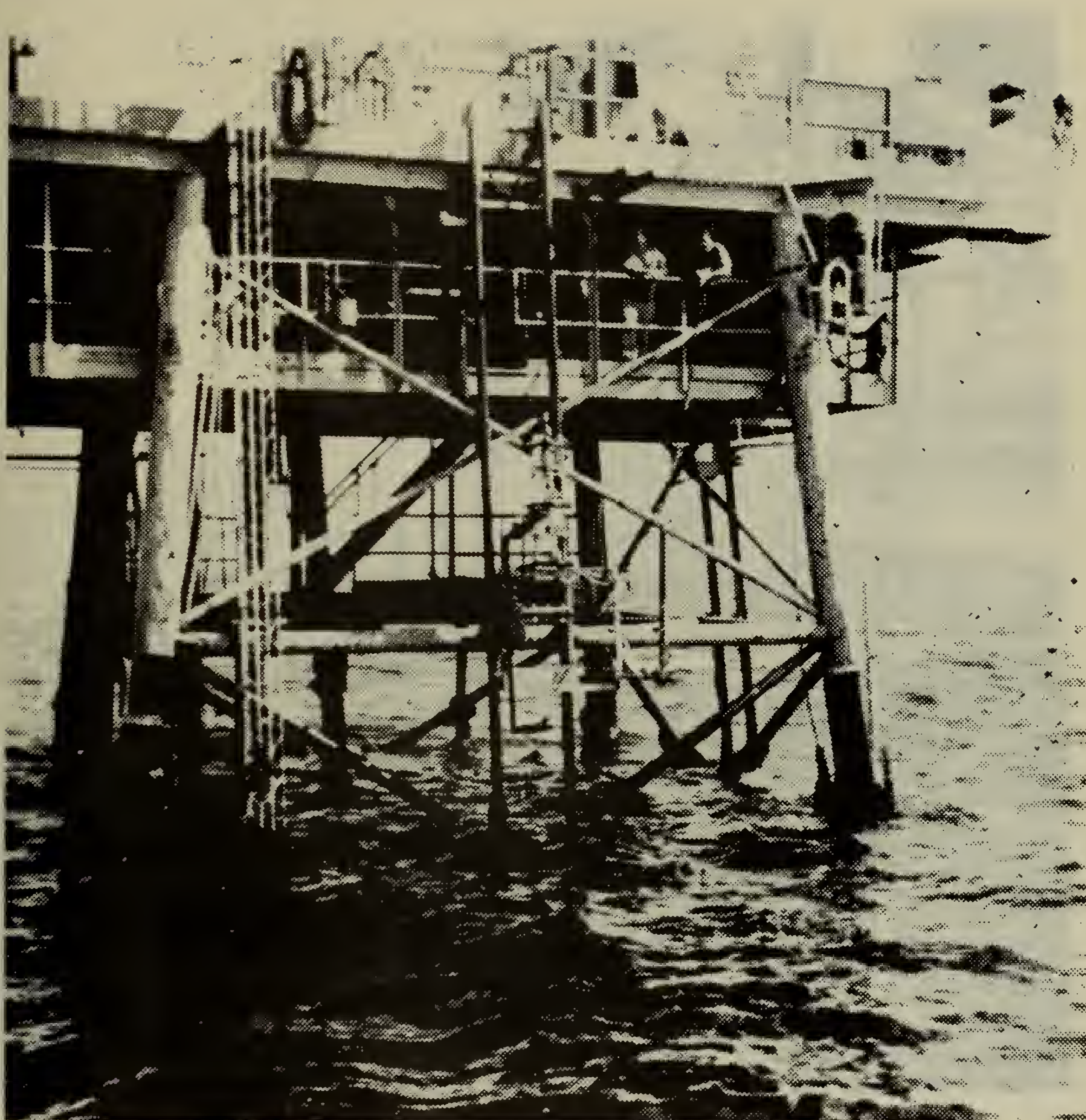
Thermistor Resistance Calibration Curve
Figure 5.



Thermistor Voltage Calibration Curve
Figure 6.

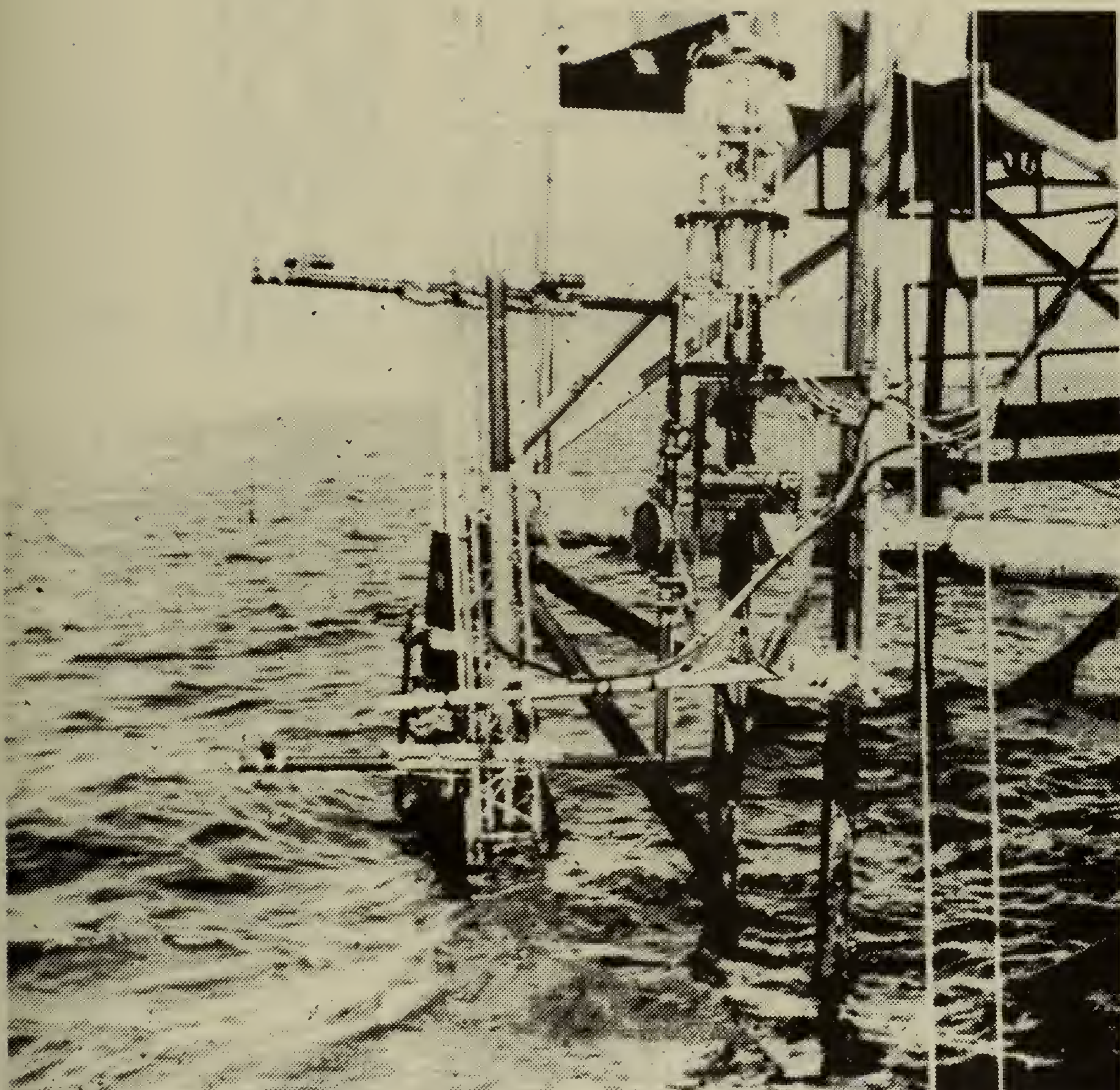


SENSOR CONFIGURATION
Figure 7.



Instrument Array

Figure 8.



Thermistor and Velocimeter Mountings

Figure 9.

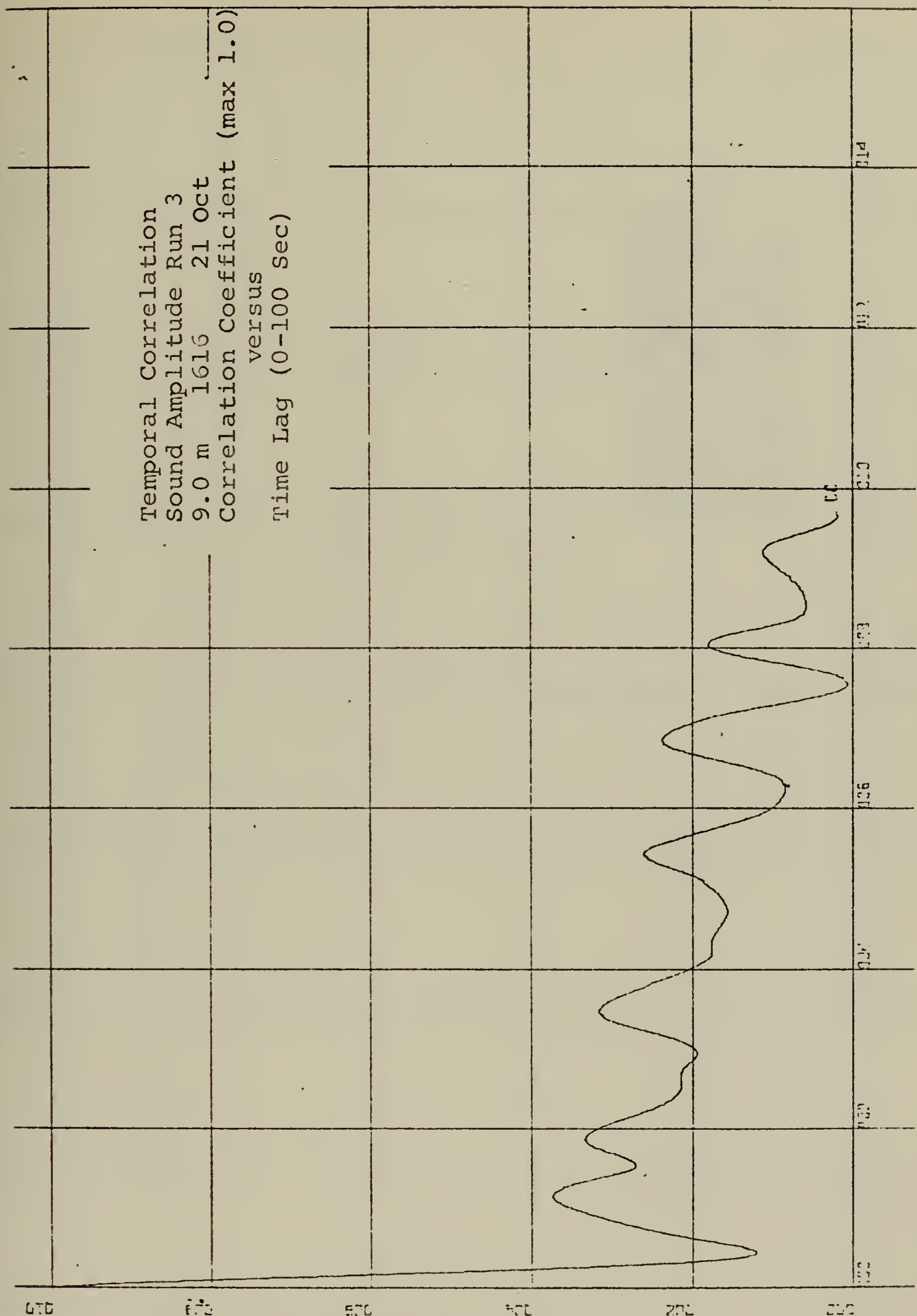

Temporal Correlation
Sound Amplitude Run 3
9.0 m 1616 21 Oct
Correlation Coefficient (max 1.0)
versus
Time Lag (0-100 Sec)

Figure 10.

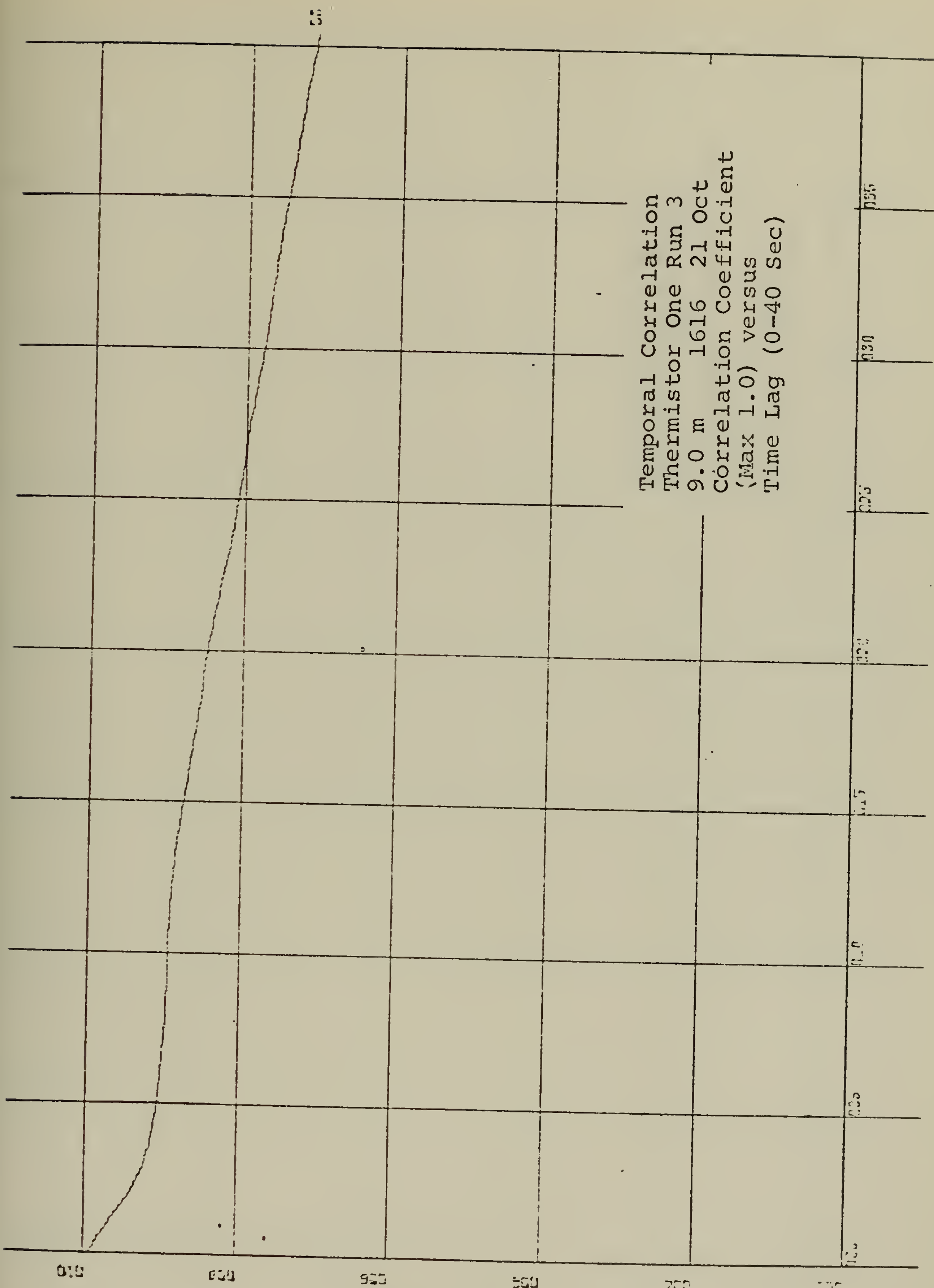

Temporal Correlation
Thermistor One Run 3
9.0 m 1616 21 Oct
Correlation Coefficient
(Max 1.0) versus
Time Lag (0-40 Sec)

Figure 11.

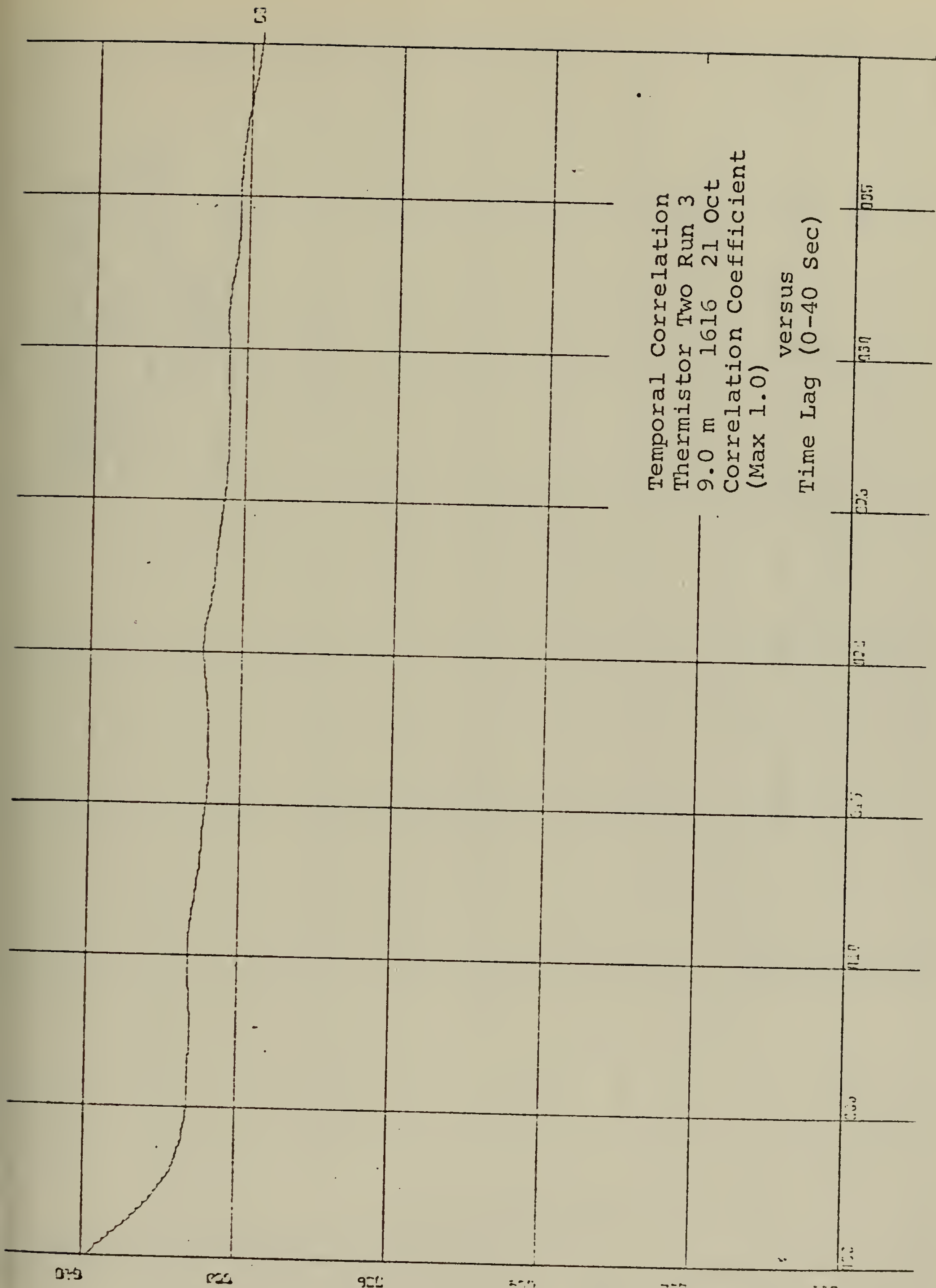

Temporal Correlation
Thermistor Two Run 3
9.0 m 1616 21 Oct
Correlation Coefficient
(Max 1.0)
versus
Time Lag (0-40 Sec)

Figure 12.

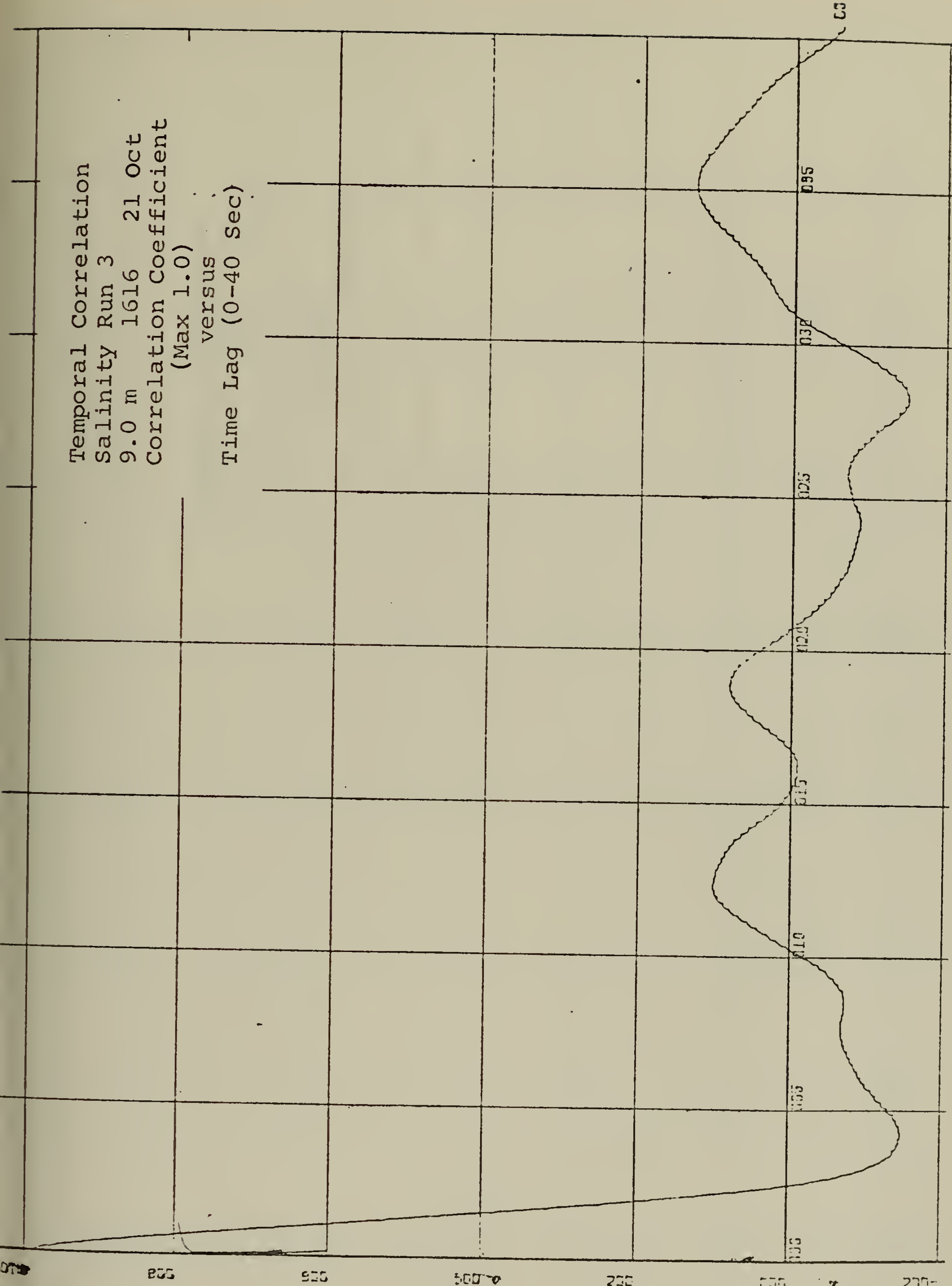

Temporal Correlation
Salinity Run 3
9.0 m 1616 21 Oct
Correlation Coefficient
(Max 1.0)
versus
Time Lag (0-40 Sec)

Figure 13.

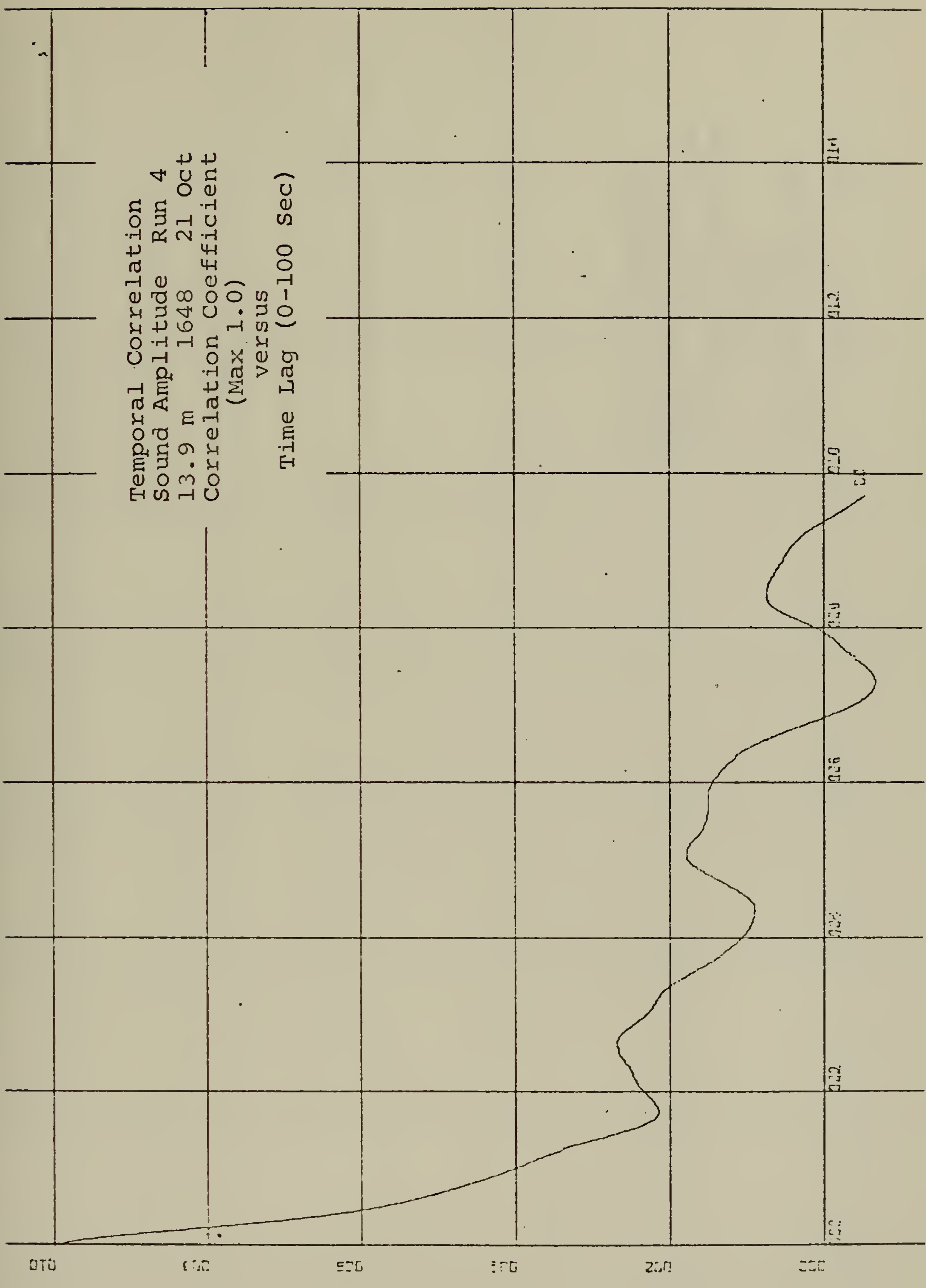

Temporal Correlation
Sound Amplitude Run 4
13.9 m 1648 21 Oct
Correlation Coefficient
(Max 1.0)
versus
Time Lag (0-100 Sec)

Figure 14.

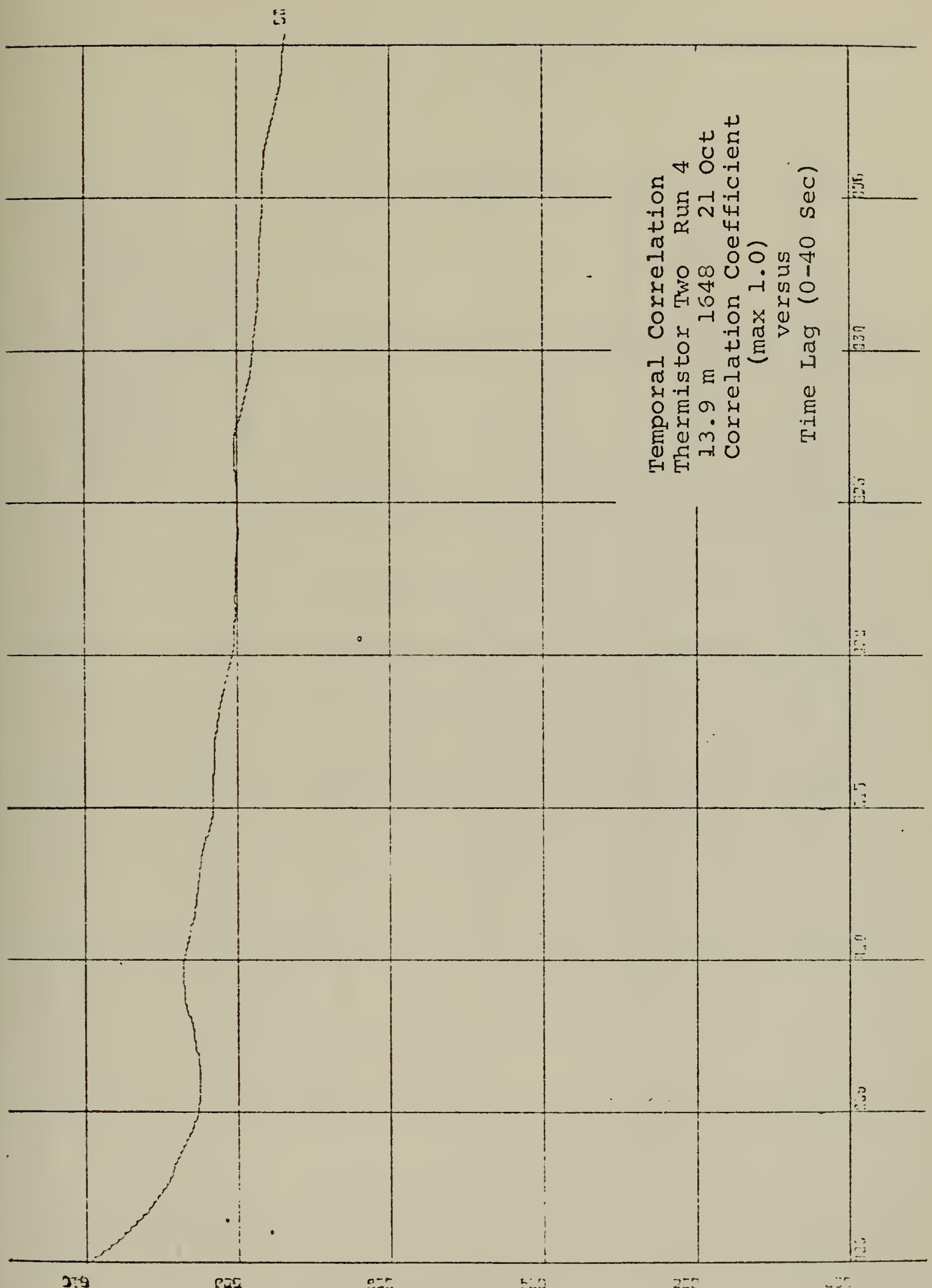

Temporal Correlation
Thermistor Two Run 4
13.9 m 1648 21 Oct
Correlation Coefficient
(max 1.0)
versus
Time Lag (0-40 Sec)

Figure 15.

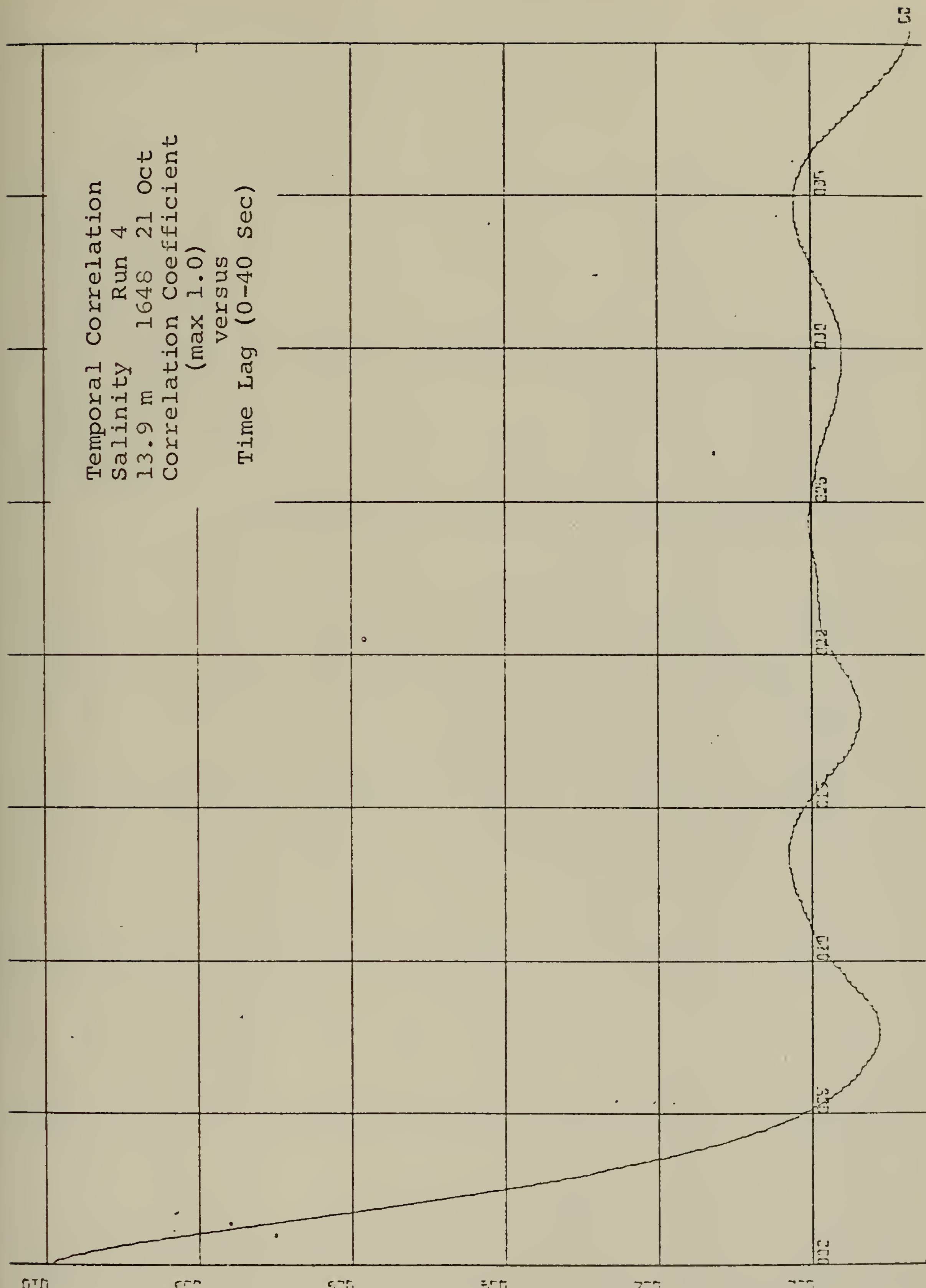

Temporal Correlation
Salinity Run 4
13.9 m 1648 21 Oct
Correlation Coefficient
(max 1.0)
versus
Time Lag (0-40 Sec)

Figure 16.

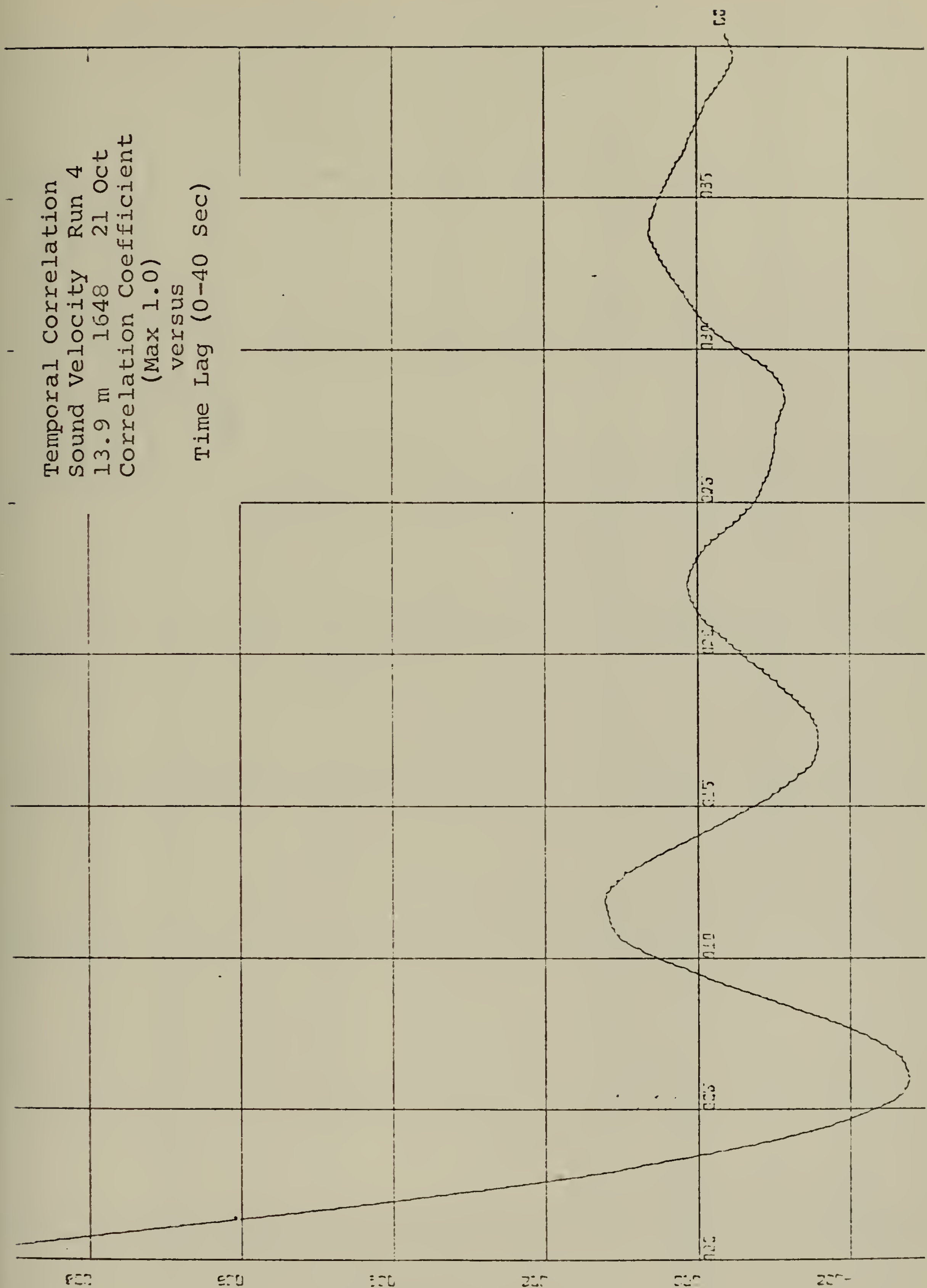

Temporal Correlation
Sound Velocity Run 4
13.9 m 1648 21 Oct
Correlation Coefficient
(Max 1.0)
versus
Time Lag (0-40 Sec)

Figure 17.

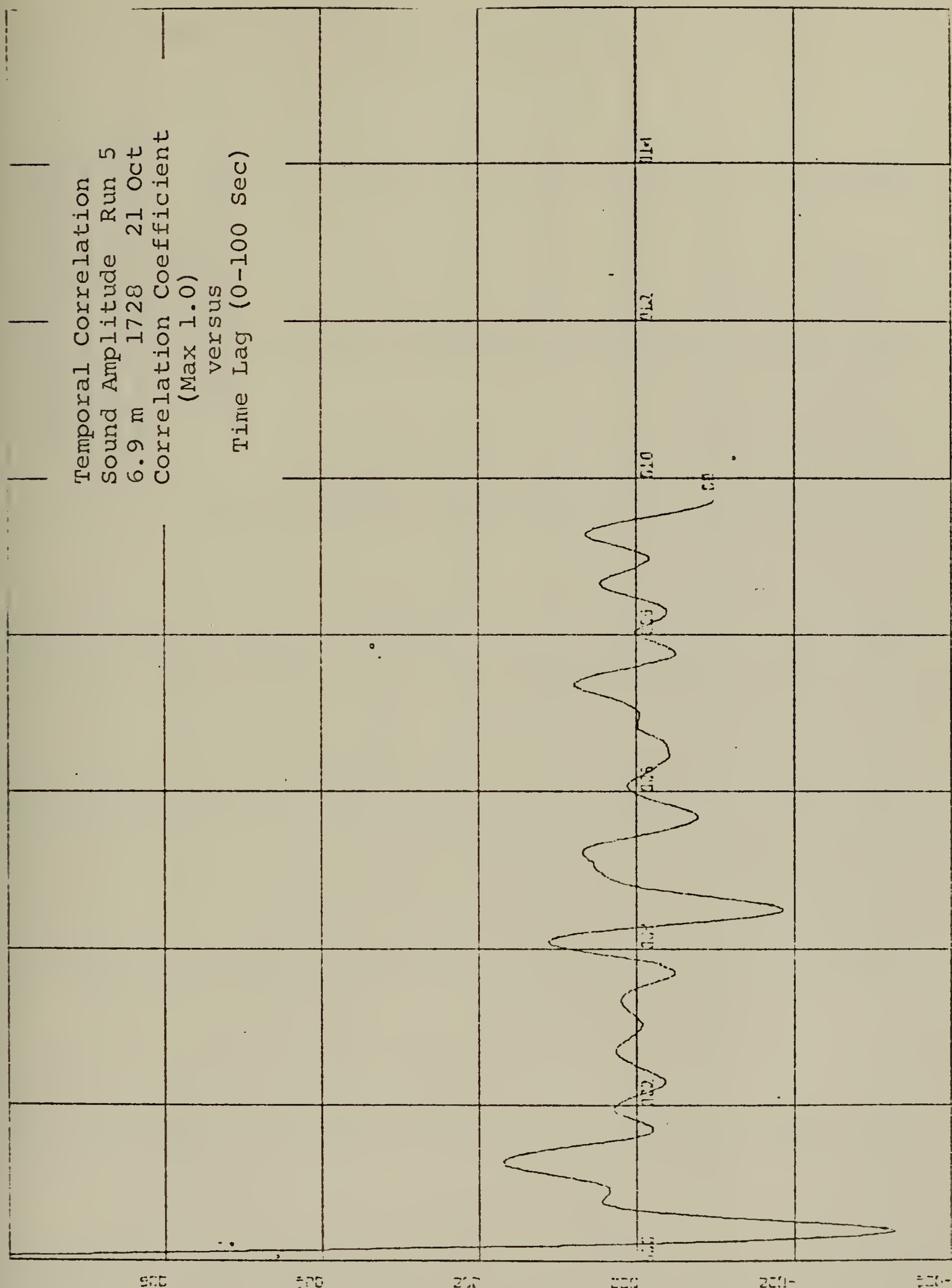

Temporal Correlation
Sound Amplitude Run 5
6.9 m 1728 21 Oct
Correlation Coefficient
(Max 1.0)
versus
Time Lag (0-100 Sec)

Figure 18.

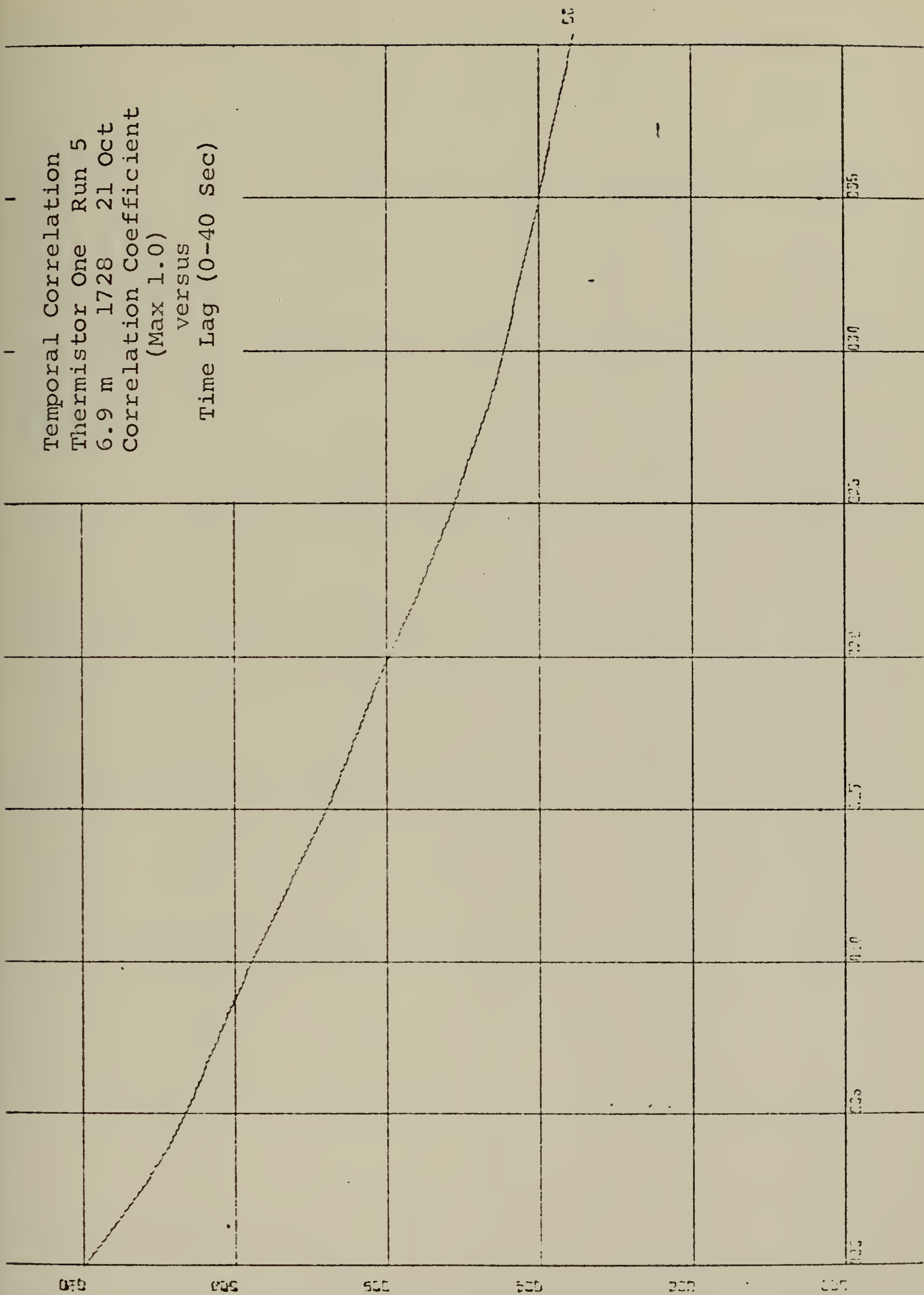

Temporal Correlation
Thermistor One Run 5
6.9 m 1728 21 Oct
Correlation Coefficient
(Max 1.0)
versus
Time Lag (0-40 Sec)

Figure 19.

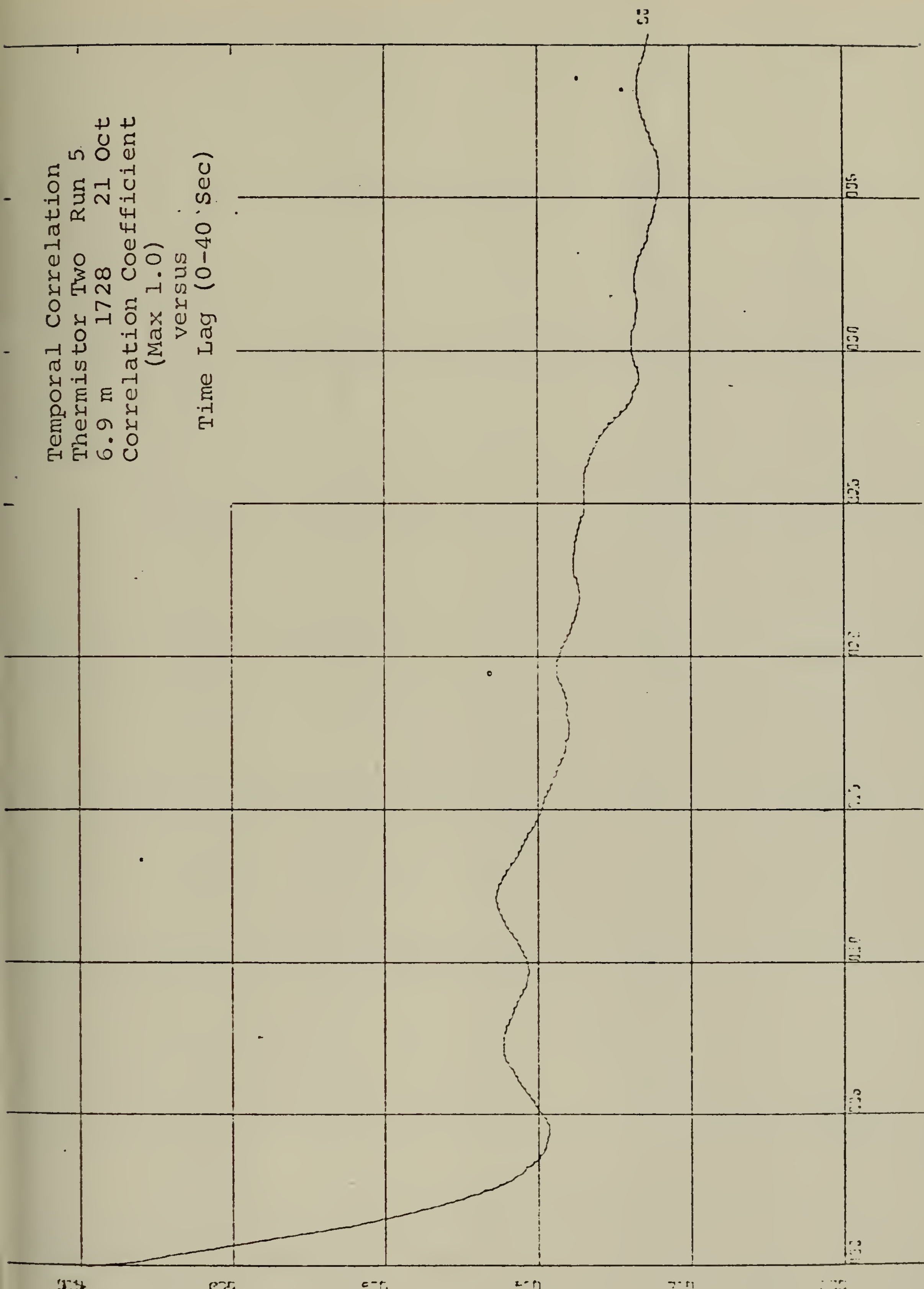
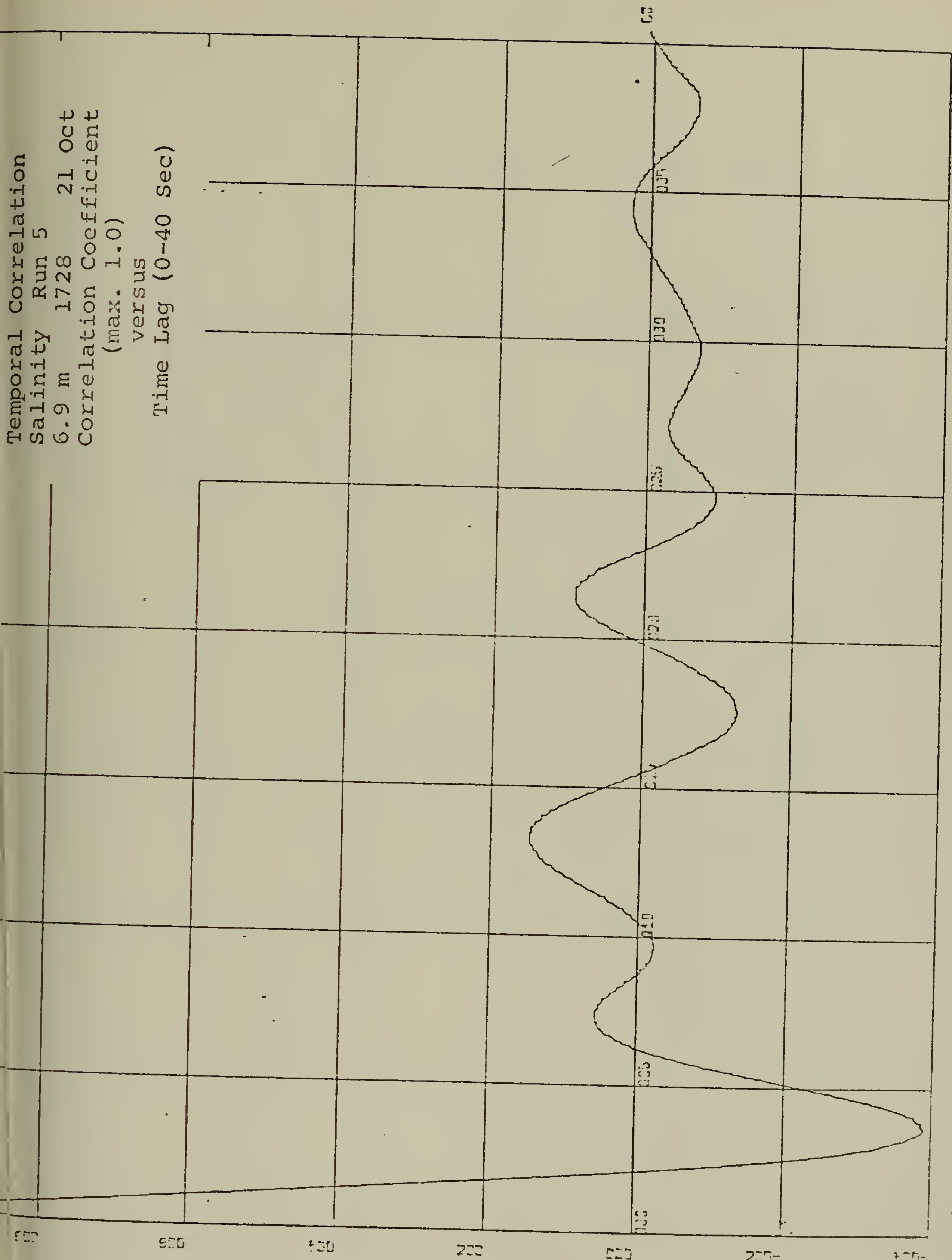

Temporal Correlation
Thermistor Two Run 5
6.9 m 1728 21 Oct
Correlation Coefficient
(Max 1.0)
versus
Time Lag (0-40 Sec)

Figure 20.



Temporal Correlation
Salinity Run 5
6.9 m 1728 21 Oct
Correlation Coefficient
(max. 1.0)
versus
Time Lag (0-40 Sec)

Figure 21.

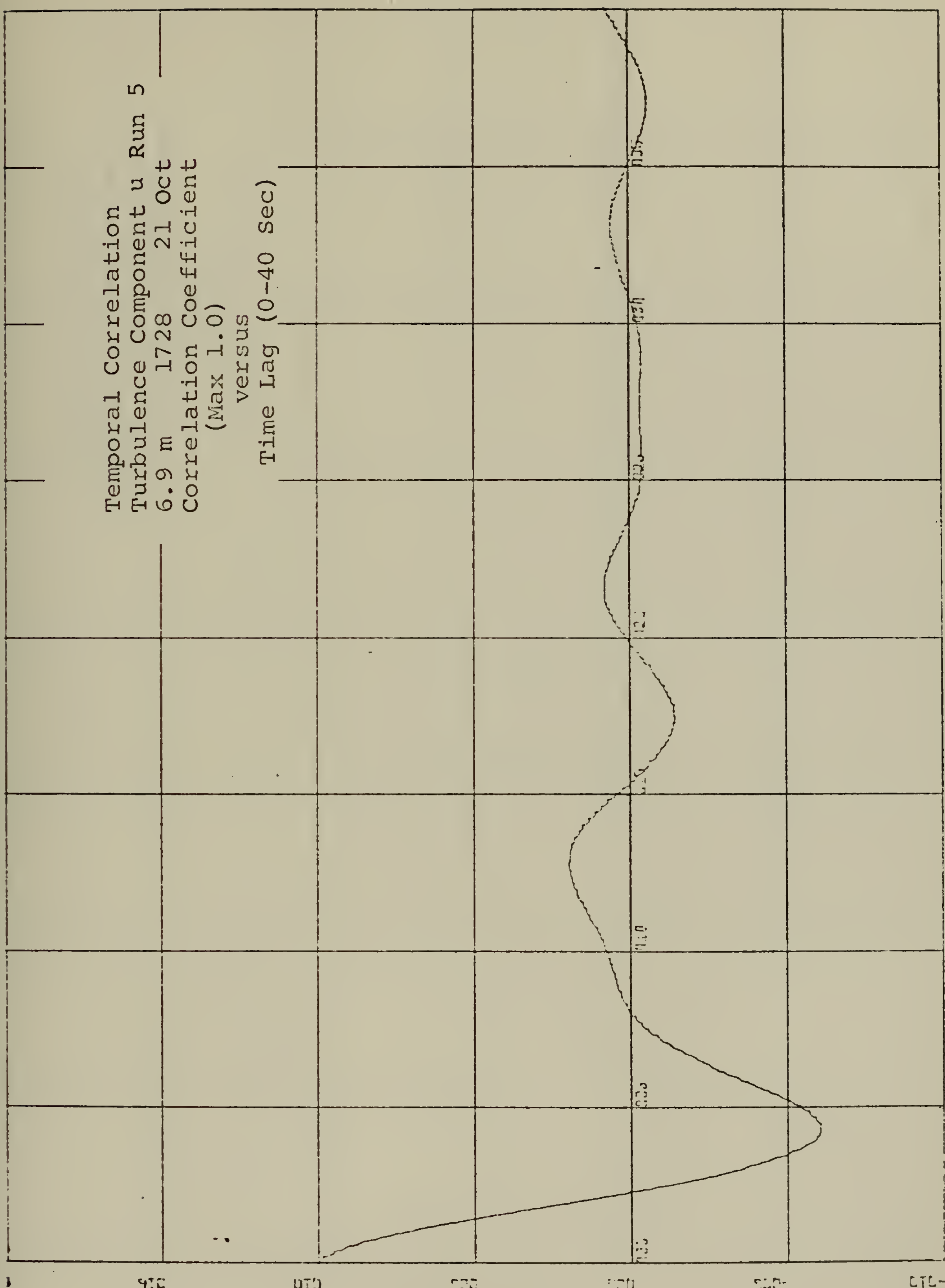

Temporal Correlation
Turbulence Component u Run 5
6.9 m 1728 21 Oct
Correlation Coefficient
(Max 1.0)
versus
Time Lag (0-40 Sec)

Figure 22.

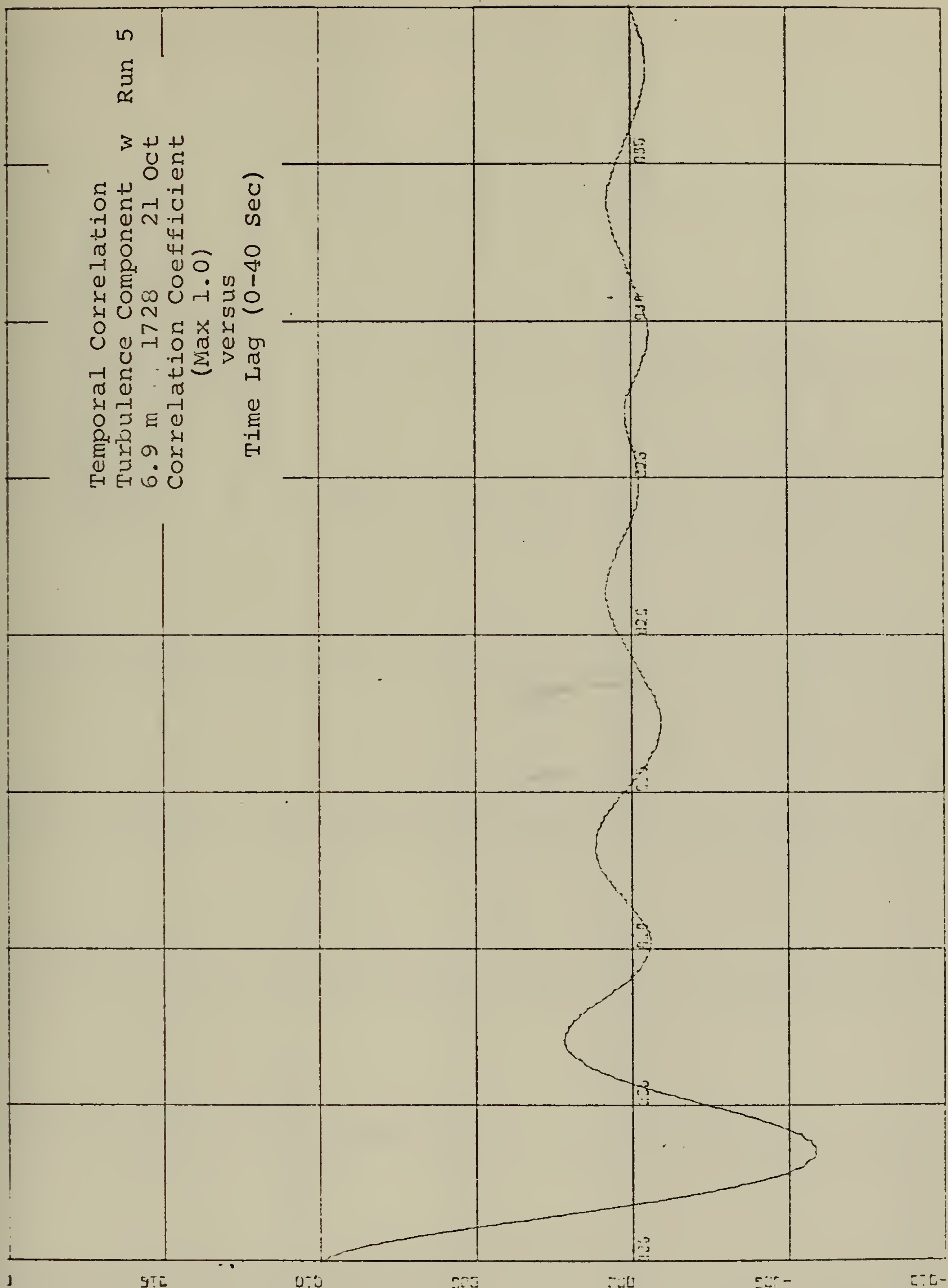

Temporal Correlation
Turbulence Component w Run 5
6.9 m 1728 21 Oct
Correlation Coefficient
(Max 1.0)
versus
Time Lag (0-40 Sec)

Figure 23.

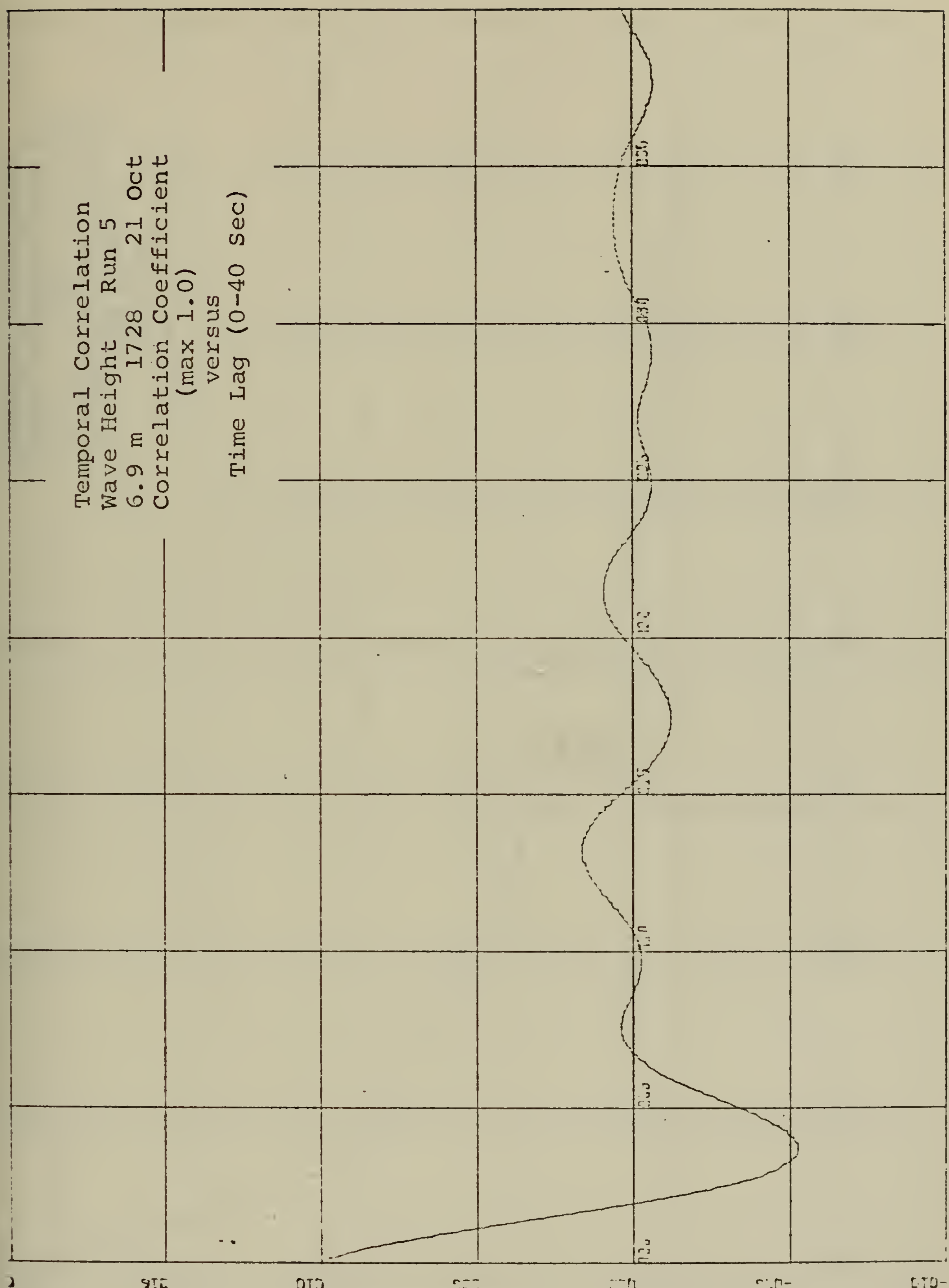

Temporal Correlation
Wave Height Run 5
6.9 m 1728 21 Oct
Correlation Coefficient
(max 1.0)
versus
Time Lag (0-40 Sec)

Figure 24.

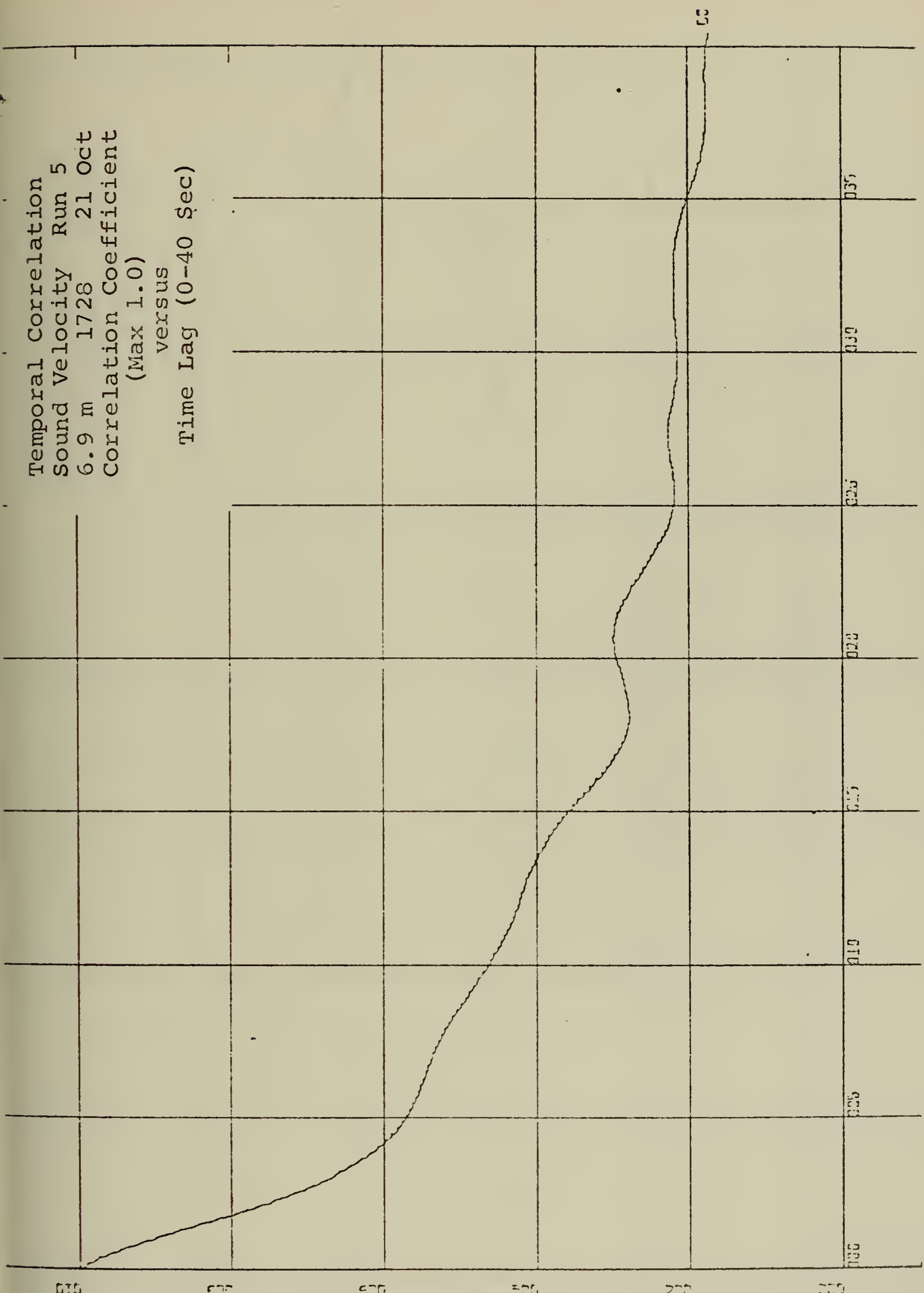

Temporal Correlation
Sound Velocity Run 5
6.9 m 1728 21 Oct
Correlation Coefficient
(Max 1.0)
versus
Time Lag (0-40 Sec)

Figure 25.

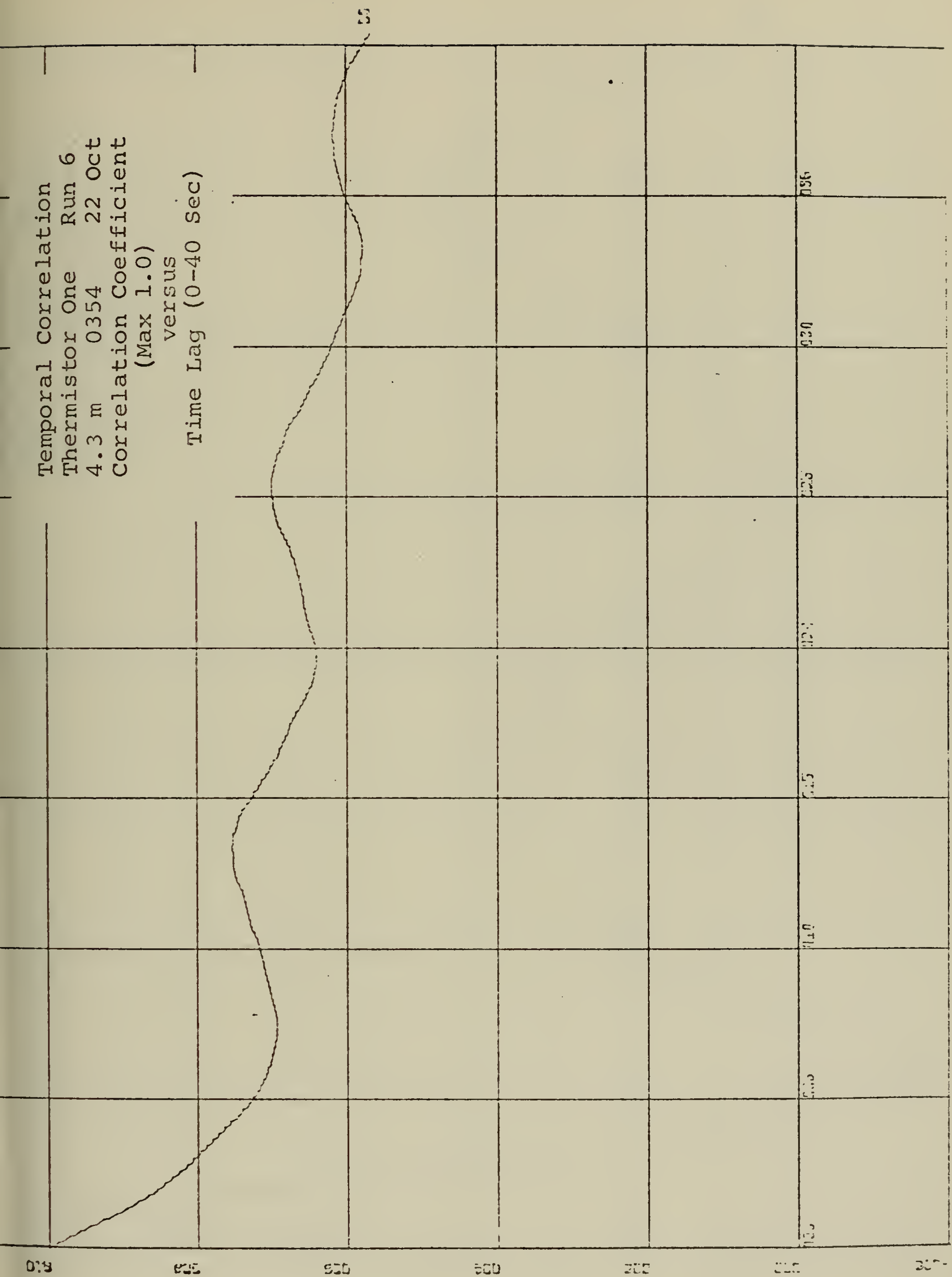

Temporal Correlation
Thermistor One Run 6
4.3 m 0354 22 Oct
Correlation Coefficient
(Max 1.0)
versus
Time Lag (0-40 Sec)

Figure 26.

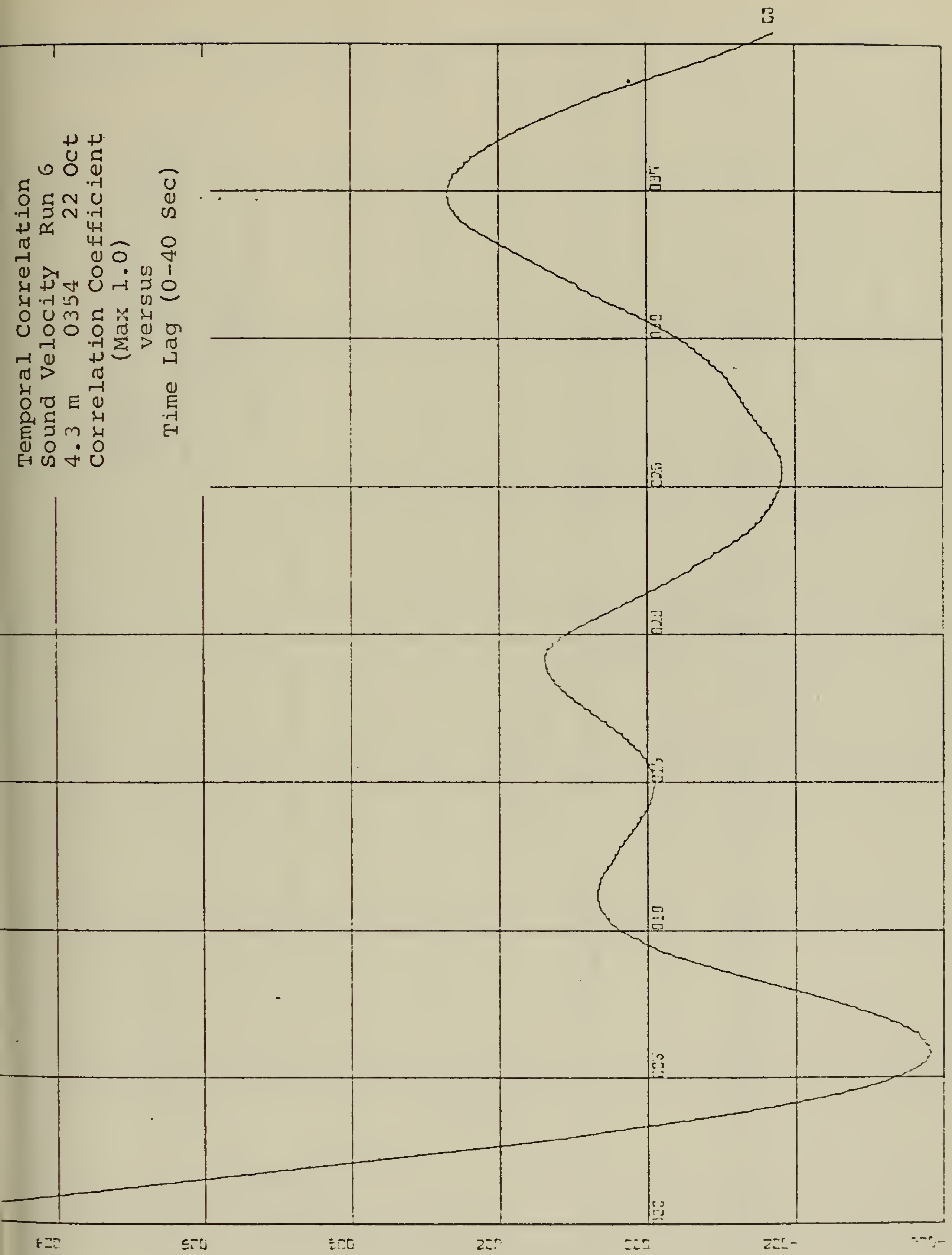

Temporal Correlation
Sound Velocity Run 6
4.3 m 0354 22 Oct
Correlation Coefficient
(Max 1.0)
versus
Time Lag (0-40 Sec)

Figure 27.

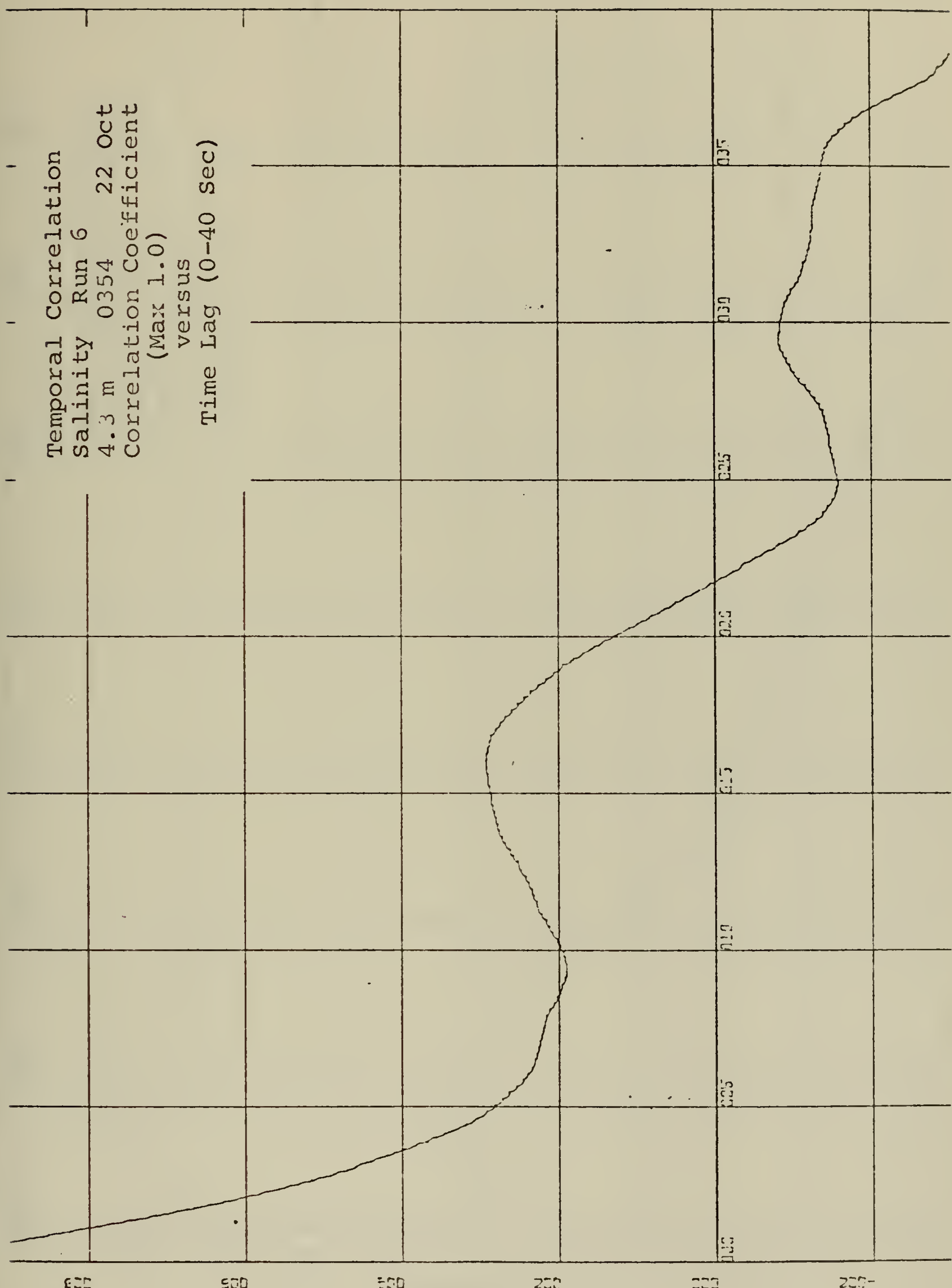

Temporal Correlation
Salinity Run 6
4.3 m 0354 22 Oct
Correlation Coefficient
(Max 1.0)
versus
Time Lag (0-40 Sec)

Figure 28.

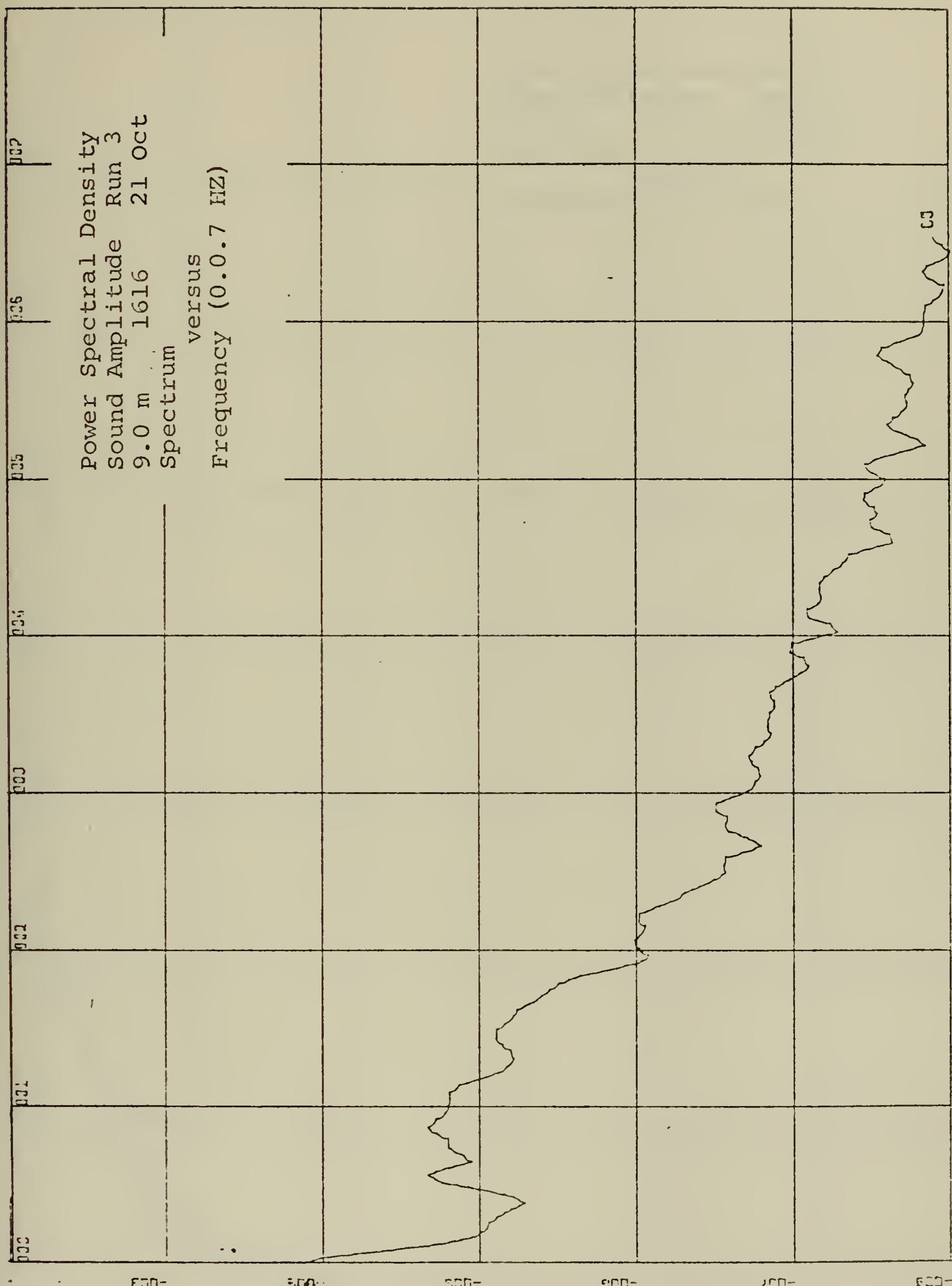

Power Spectral Density
Sound Amplitude Run 3
9.0 m 1616 21 Oct
Spectrum
versus
Frequency (0.0.7 HZ)

Figure 29.

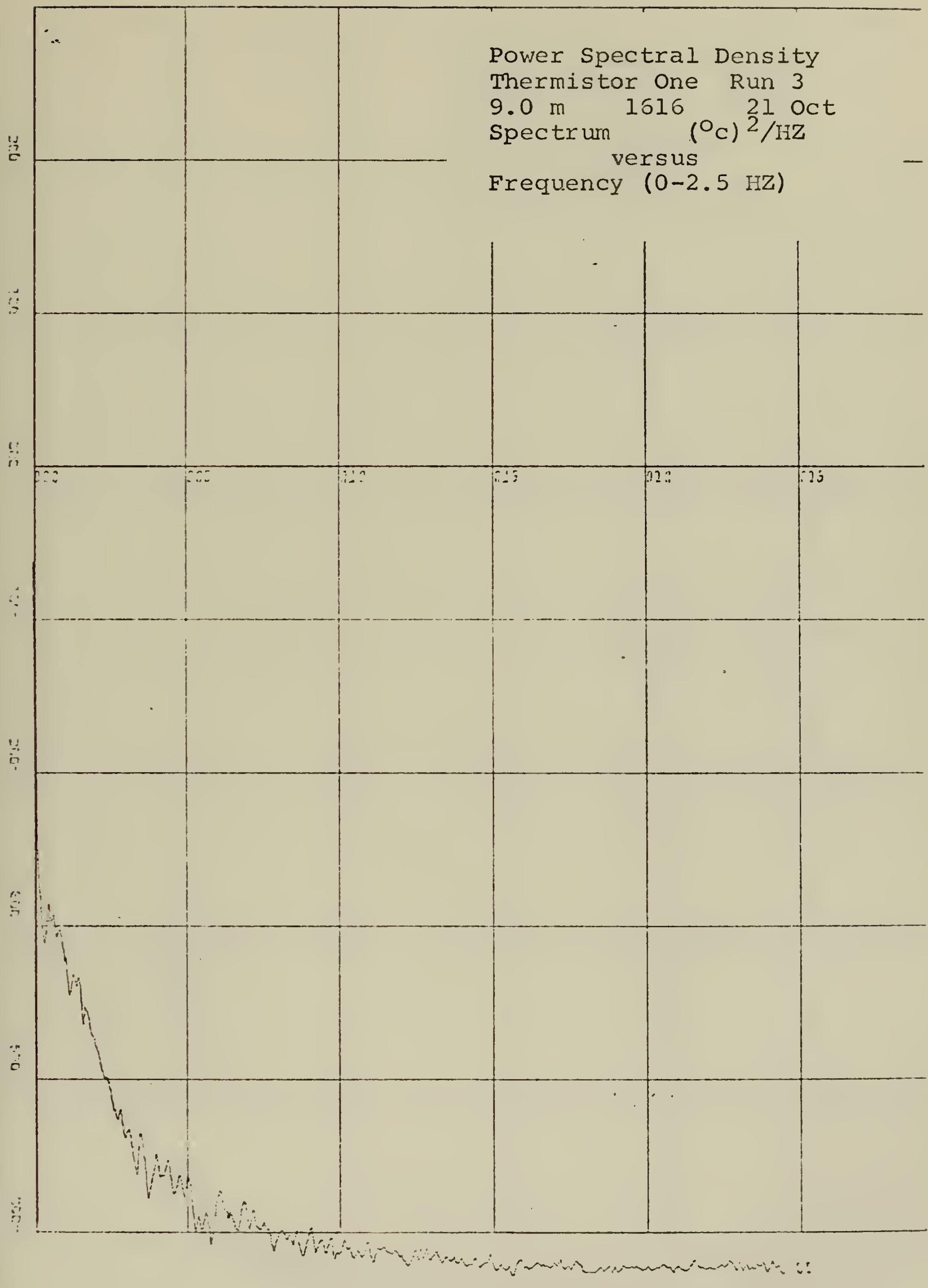

Power Spectral Density
Thermistor One Run 3
9.0 m 1616 21 Oct
Spectrum (°c)²/HZ
versus
Frequency (0-2.5 HZ)

Figure 30.

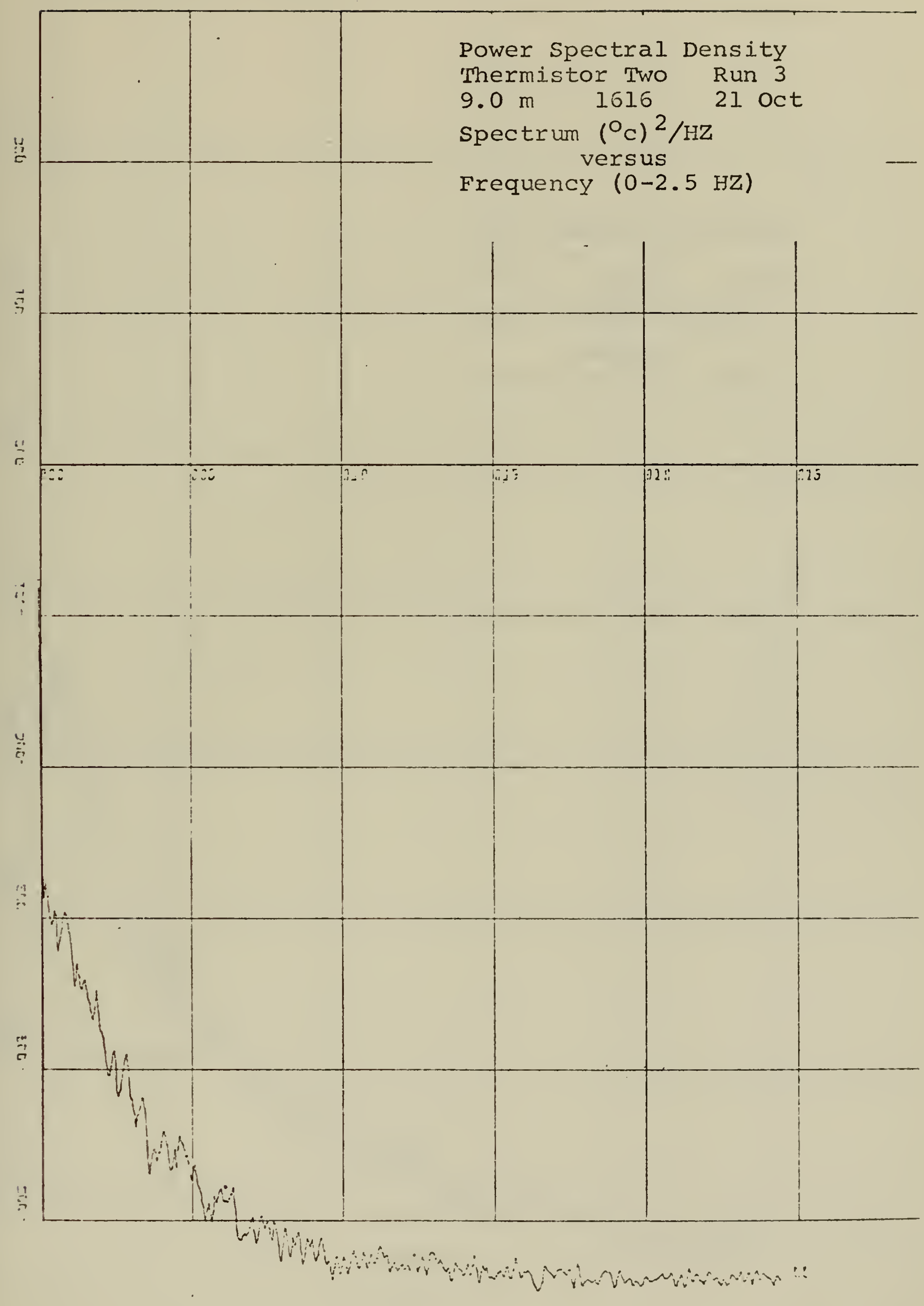
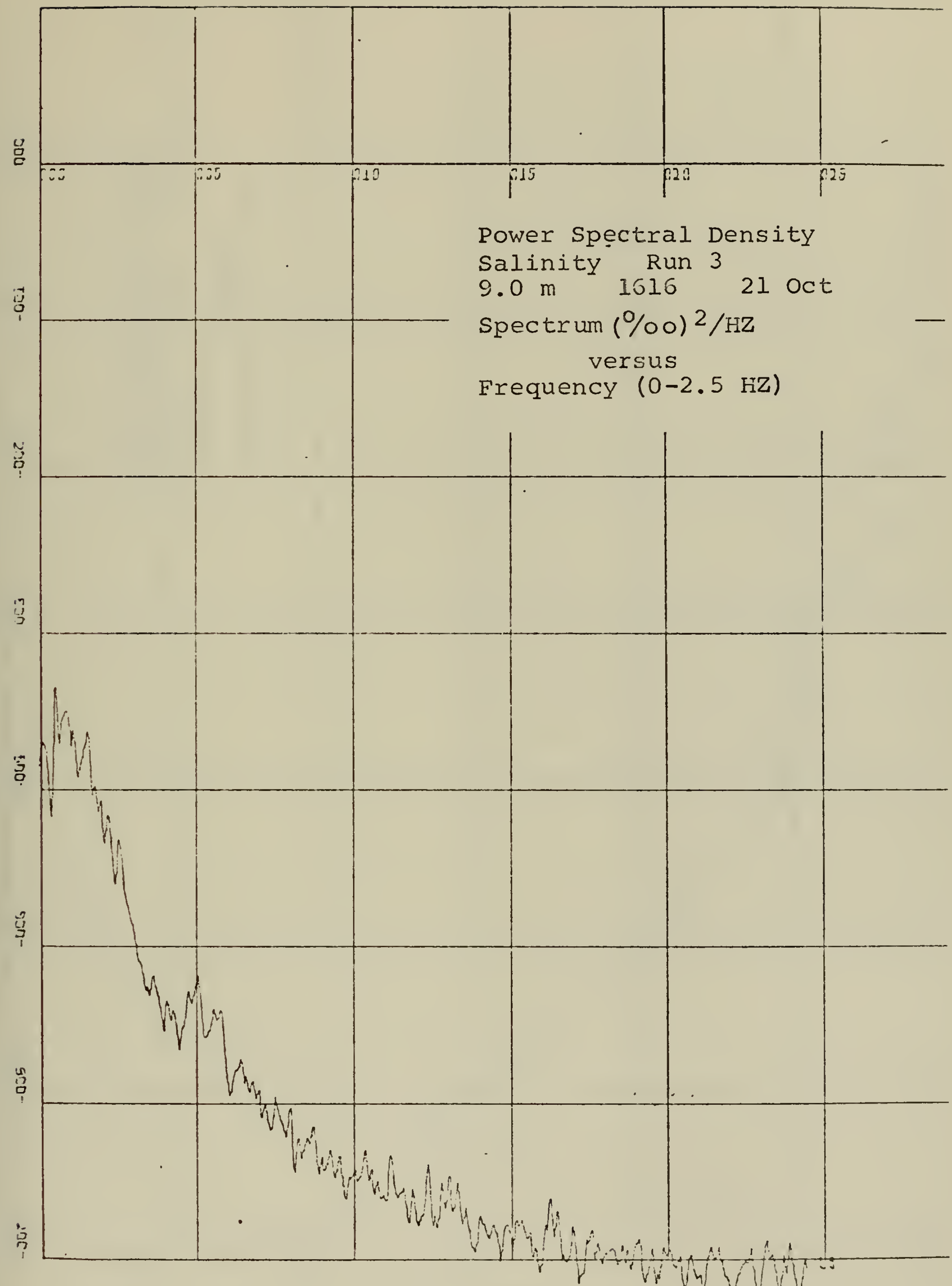

Power Spectral Density
Thermistor Two Run 3
9.0 m 1616 21 Oct
Spectrum $(^{o}c)^{2}$/HZ
versus
Frequency (0-2.5 HZ)

Figure 31.



Power Spectral Density
Salinity Run 3
9.0 m 1616 21 Oct
Spectrum (°/oo)²/HZ
versus
Frequency (0-2.5 HZ)

Figure 32.

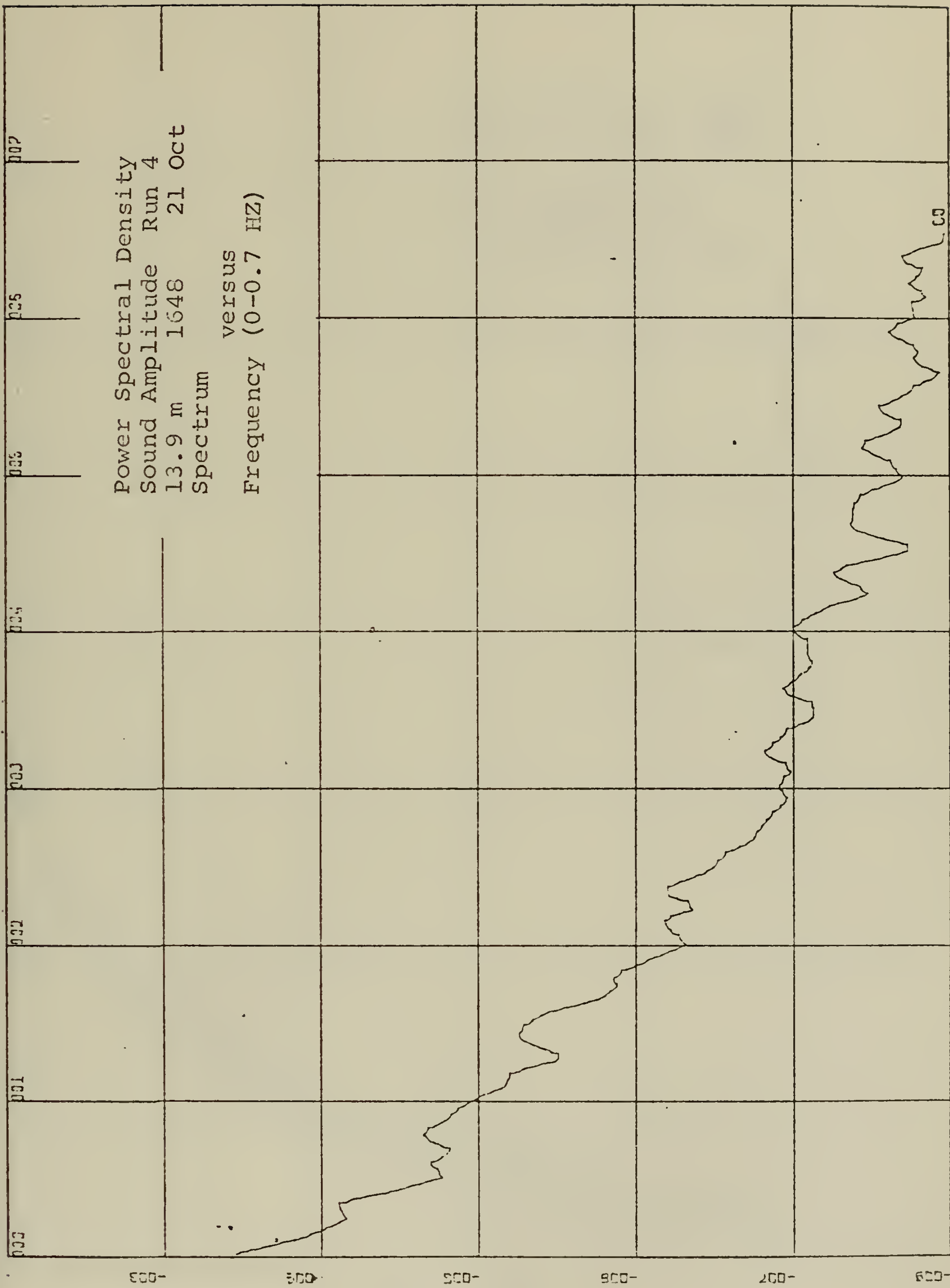

Power Spectral Density
Sound Amplitude Run 4
13.9 m 1648 21 Oct
Spectrum versus
Frequency (0-0.7 HZ)

Figure 33.

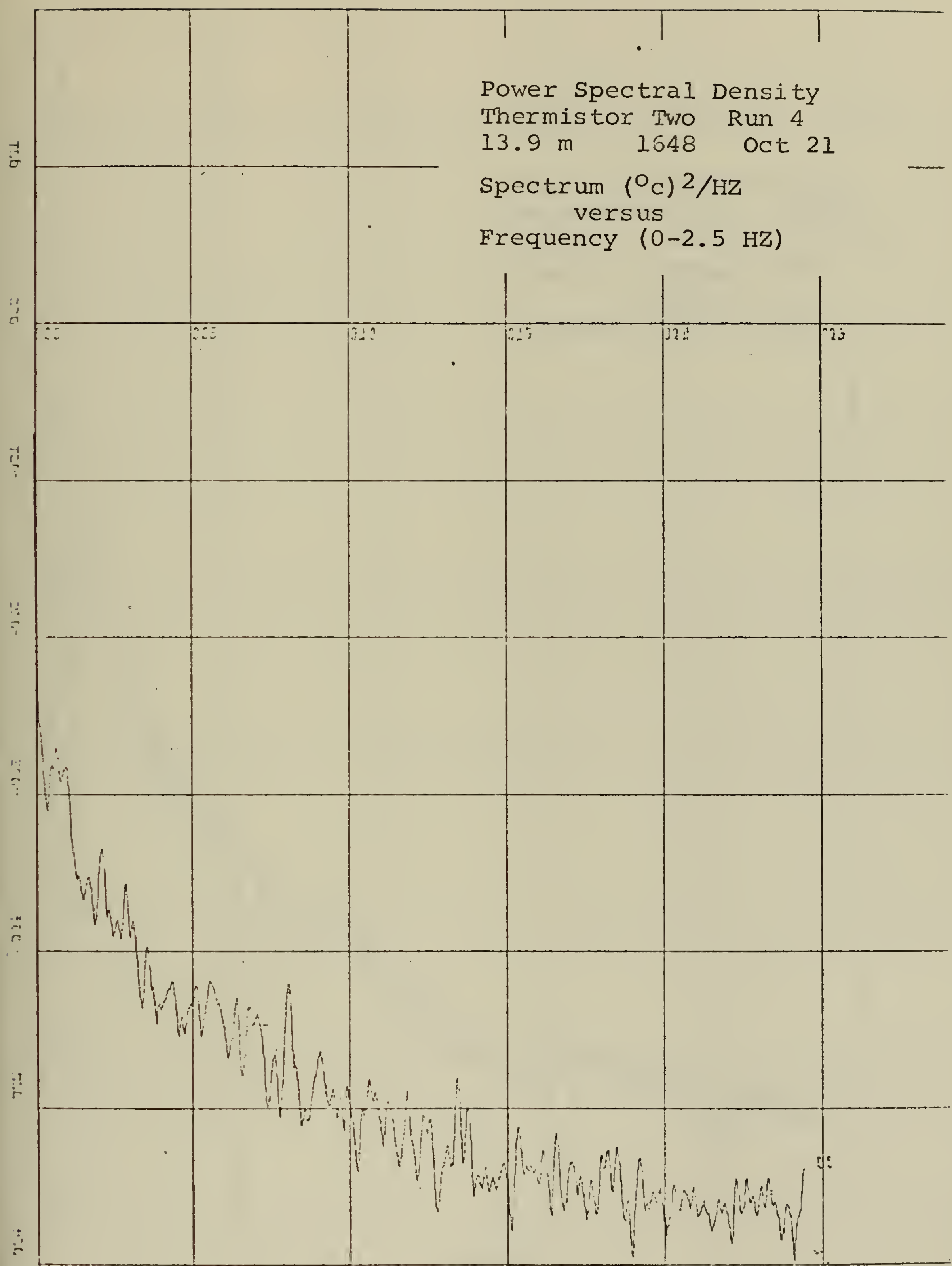

Power Spectral Density
Thermistor Two Run 4
13.9 m 1648 Oct 21
Spectrum (^{o}c)^{2}/HZ
versus
Frequency (0-2.5 HZ)

Figure 34.

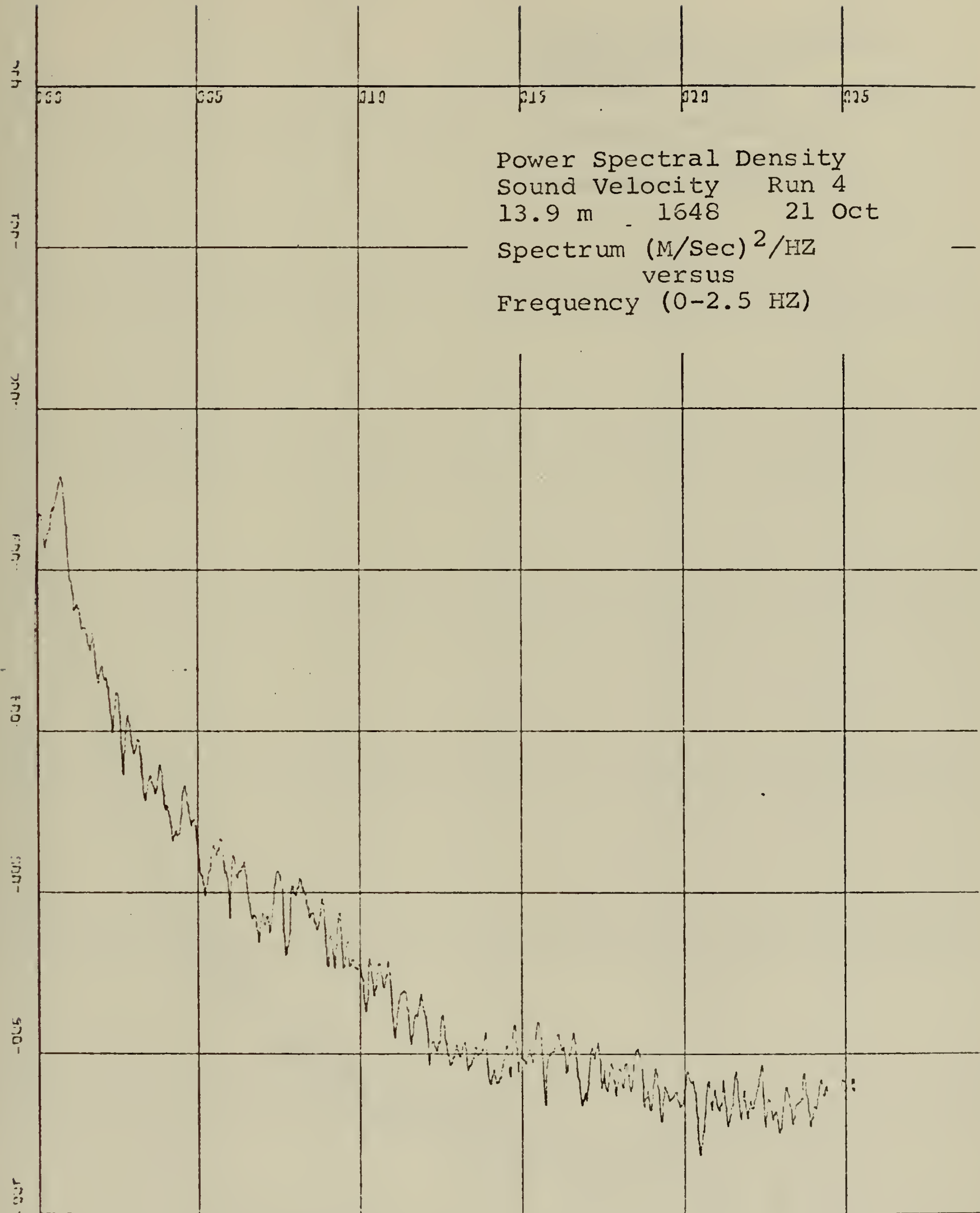

Power Spectral Density
Sound Velocity Run 4
13.9 m 1648 21 Oct
Spectrum (M/Sec)2/HZ
versus
Frequency (0-2.5 HZ)

Figure 35.

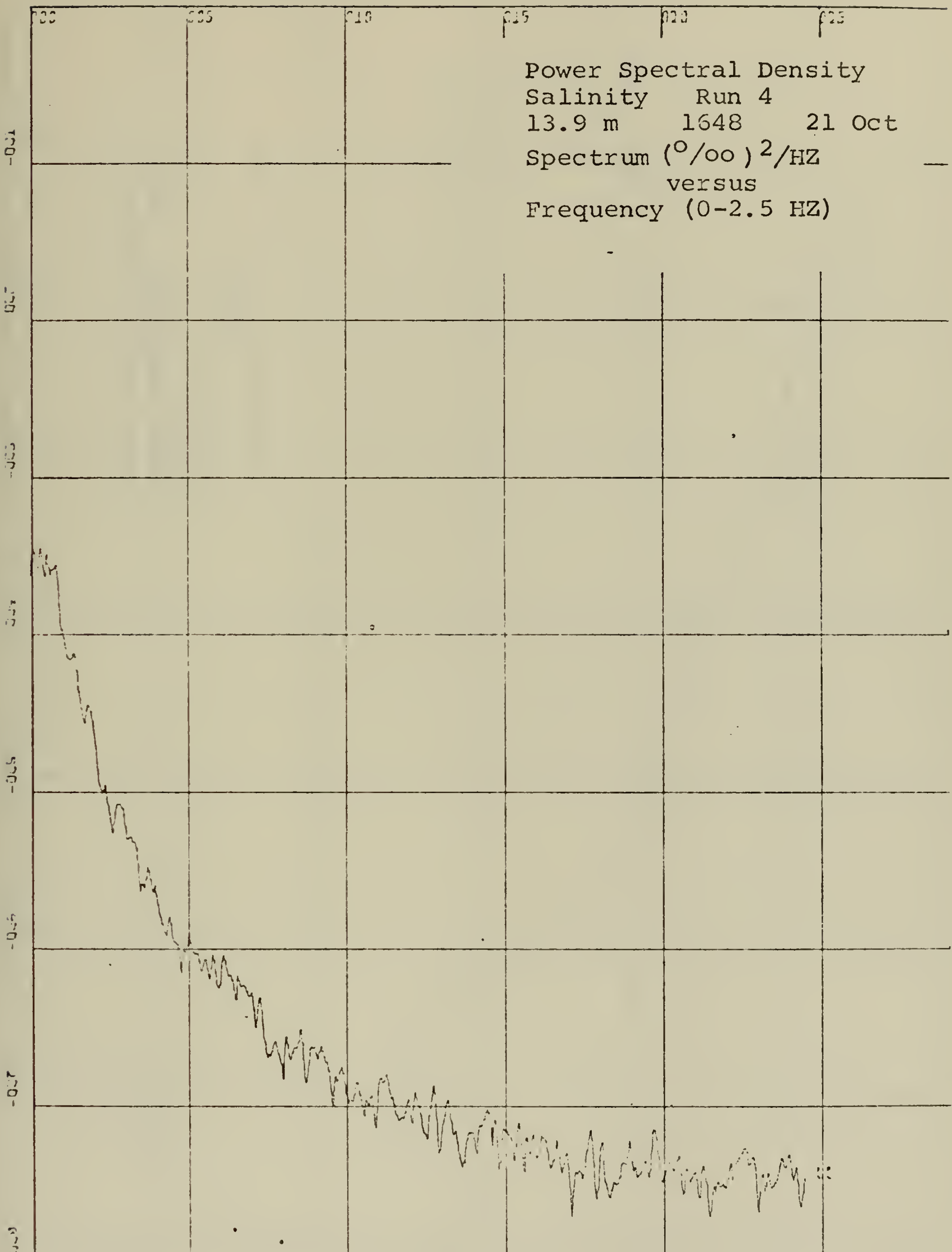

Power Spectral Density
Salinity Run 4
13.9 m 1648 21 Oct
Spectrum ($^{o}/oo$)^2/HZ
versus
Frequency (0-2.5 HZ)

Figure 36.

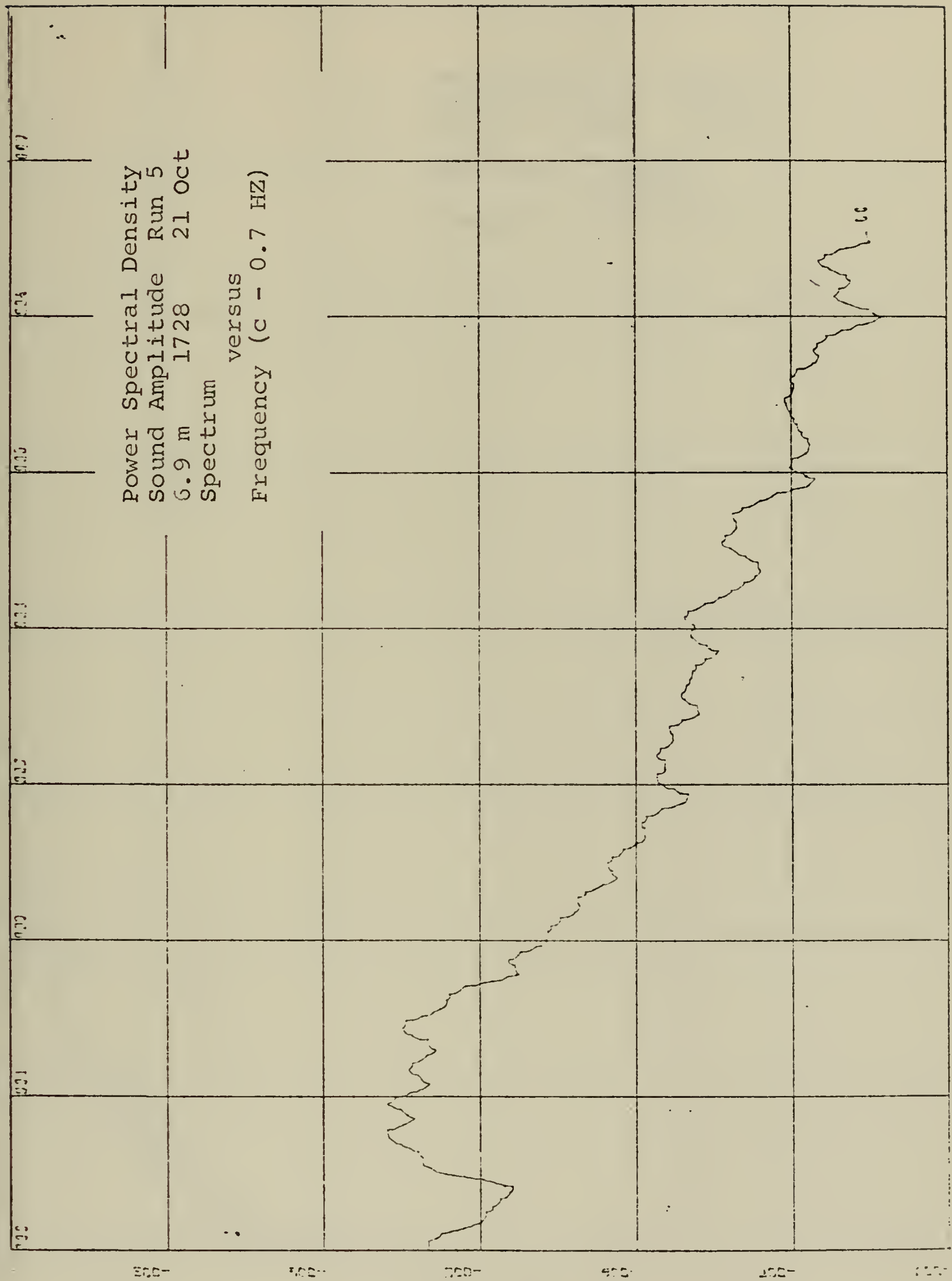

Power Spectral Density
Sound Amplitude Run 5
6.9 m 1728 21 Oct
Spectrum
versus
Frequency (c - 0.7 HZ)

Figure 37.

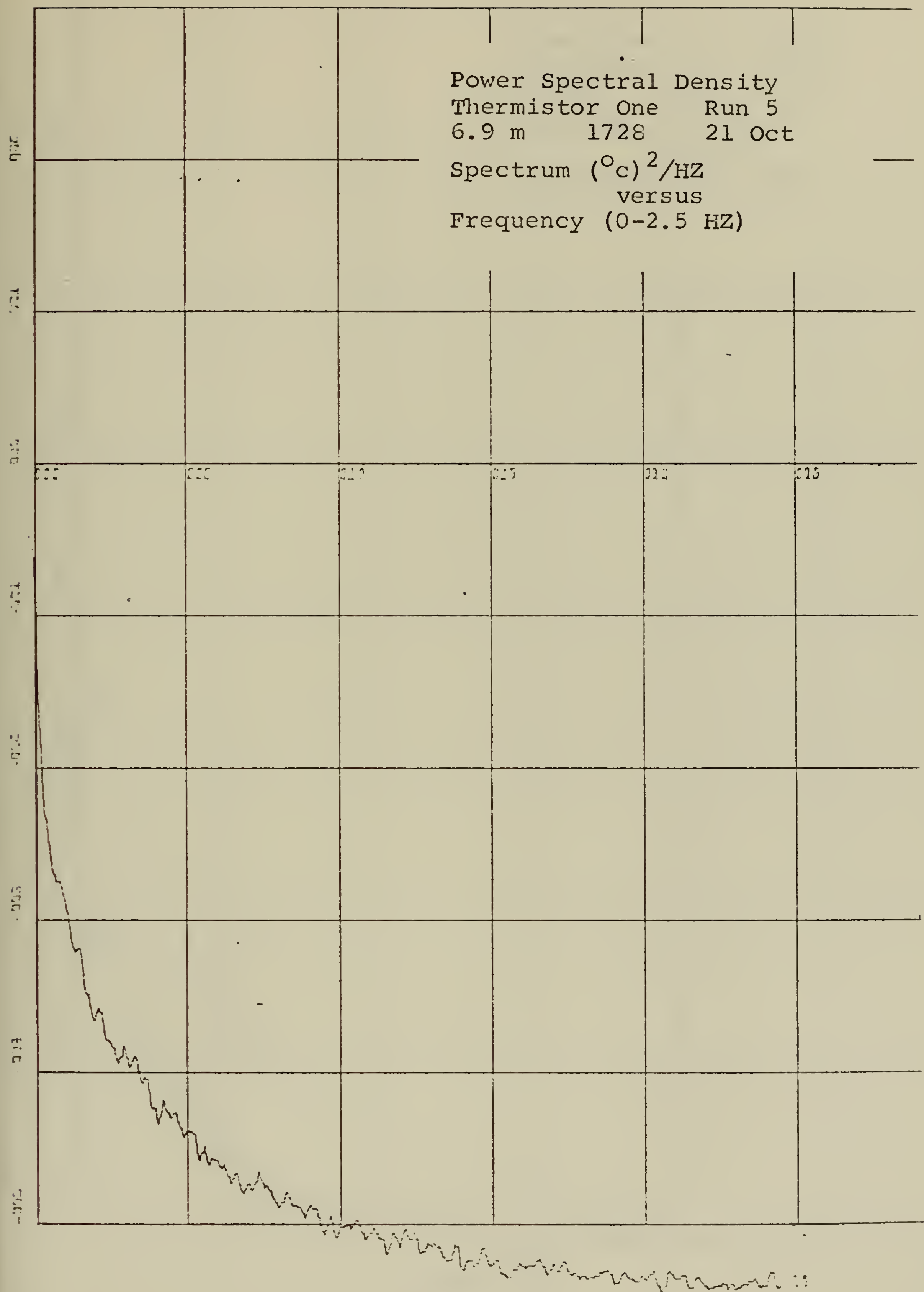

Power Spectral Density
Thermistor One Run 5
6.9 m 1728 21 Oct
Spectrum $(^{o}c)^{2}$/HZ
versus
Frequency (0-2.5 HZ)

Figure 38.

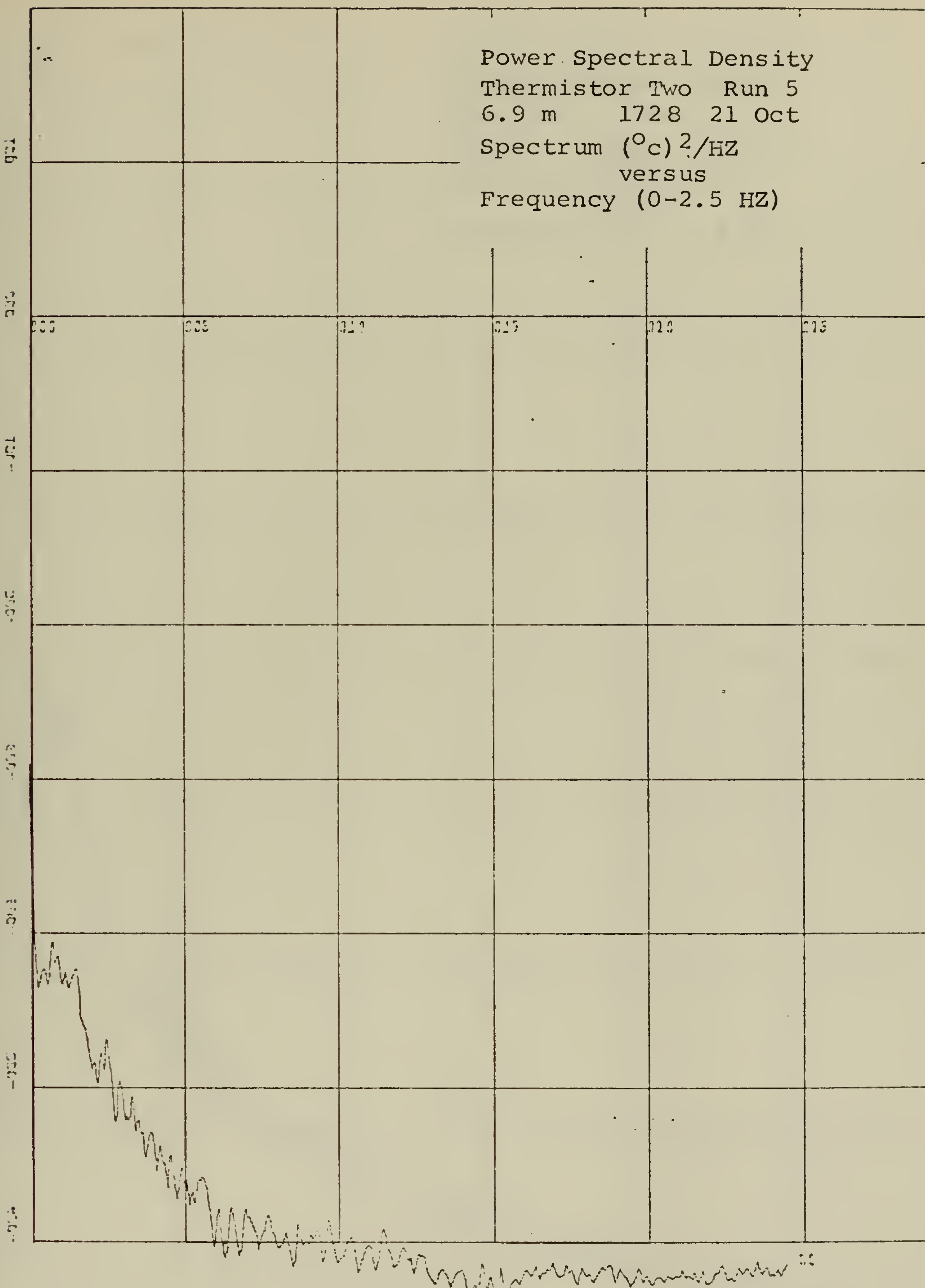

Power Spectral Density
Thermistor Two Run 5
6.9 m 1728 21 Oct
Spectrum (°c)²/HZ
versus
Frequency (0-2.5 HZ)

Figure 39.

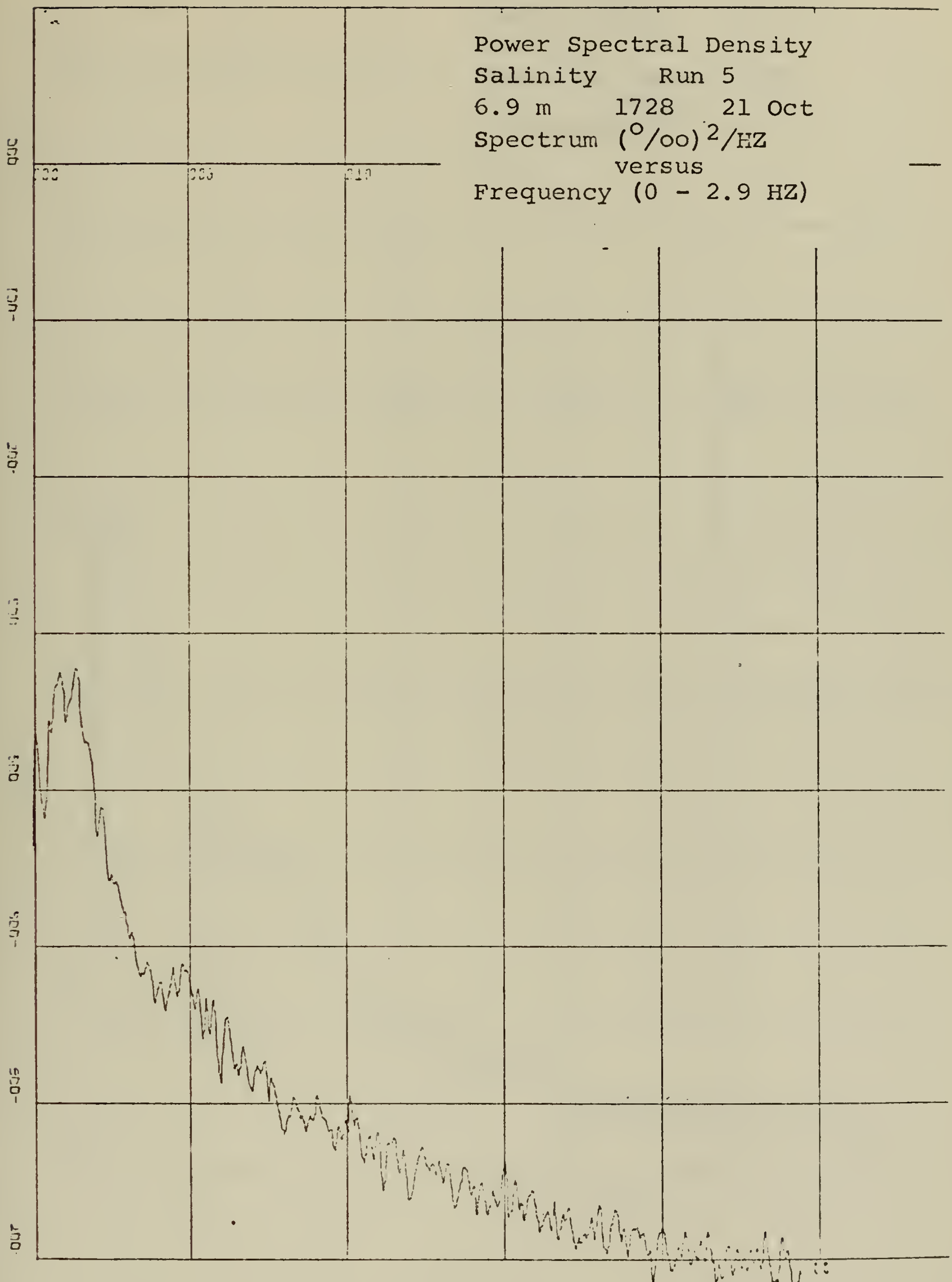

Power Spectral Density
Salinity Run 5
6.9 m 1728 21 Oct
Spectrum (°/oo)^2/HZ
versus
Frequency (0 - 2.9 HZ)

Figure 40.

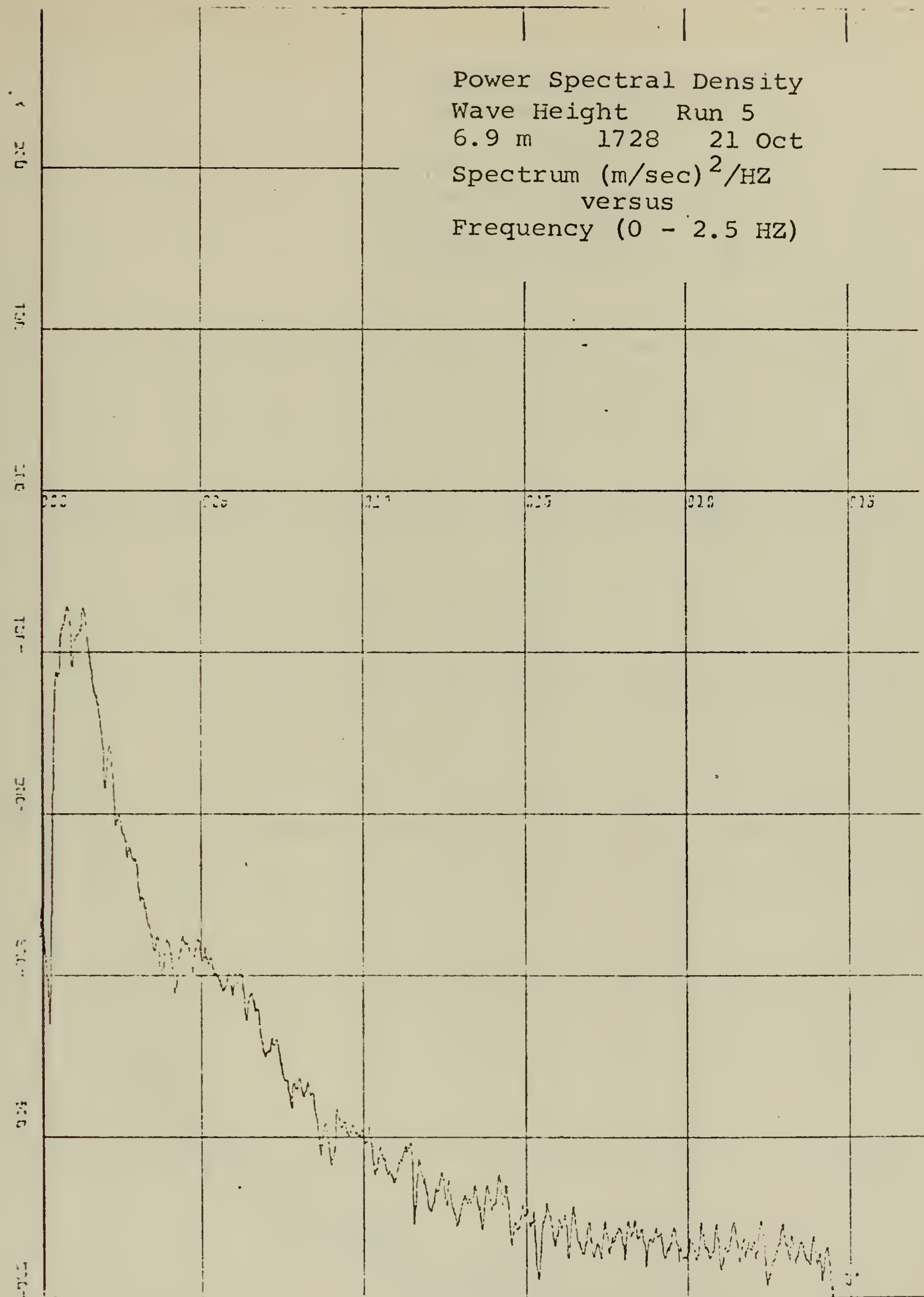

Power Spectral Density
Wave Height Run 5
6.9 m 1728 21 Oct
Spectrum (m/sec)^2/HZ
versus
Frequency (0 - 2.5 HZ)

Figure 41.

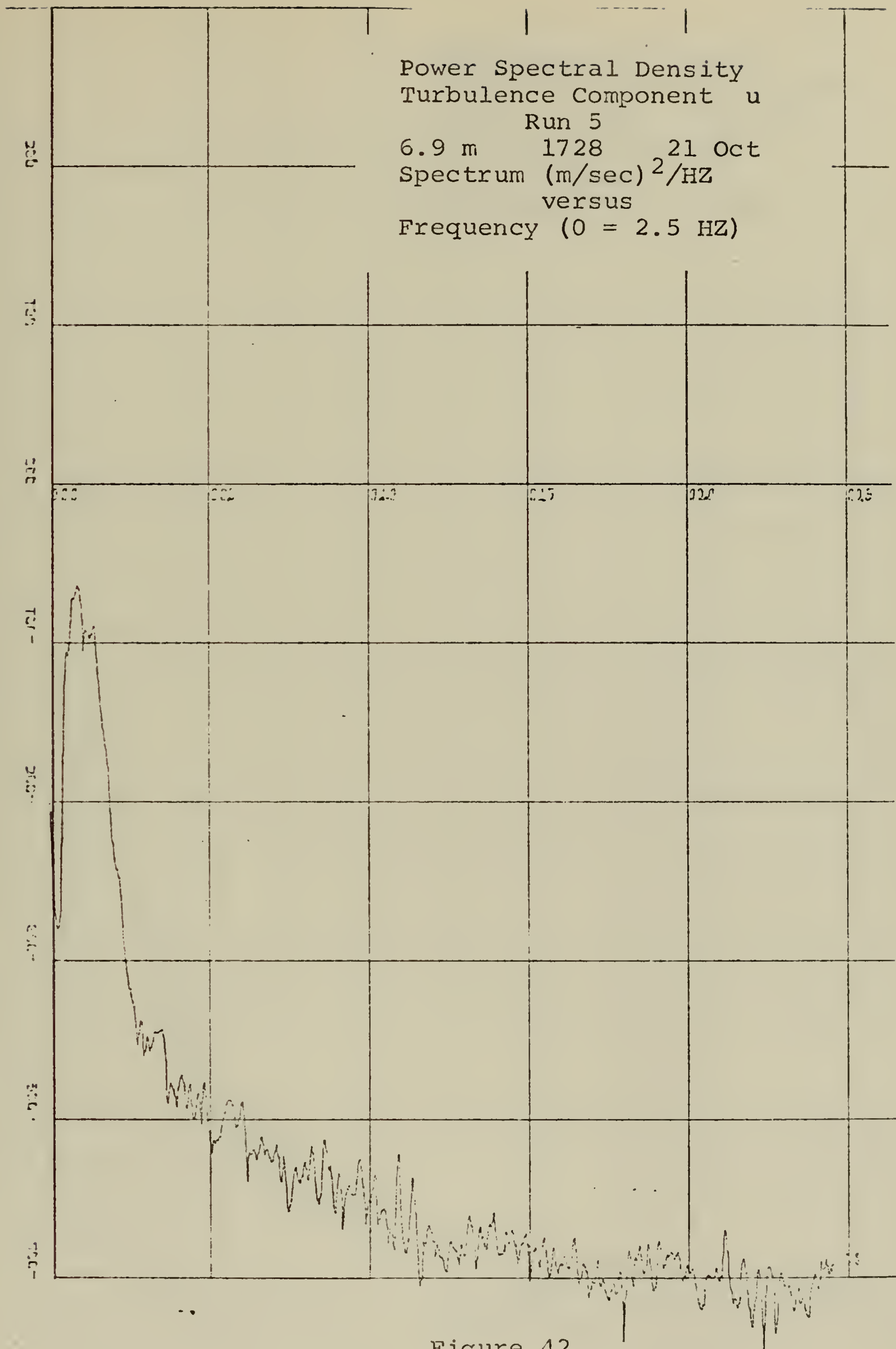

Power Spectral Density
Turbulence Component u
Run 5
6.9 m 1728 21 Oct
Spectrum (m/sec)^2/HZ
versus
Frequency (0 = 2.5 HZ)

Figure 42.

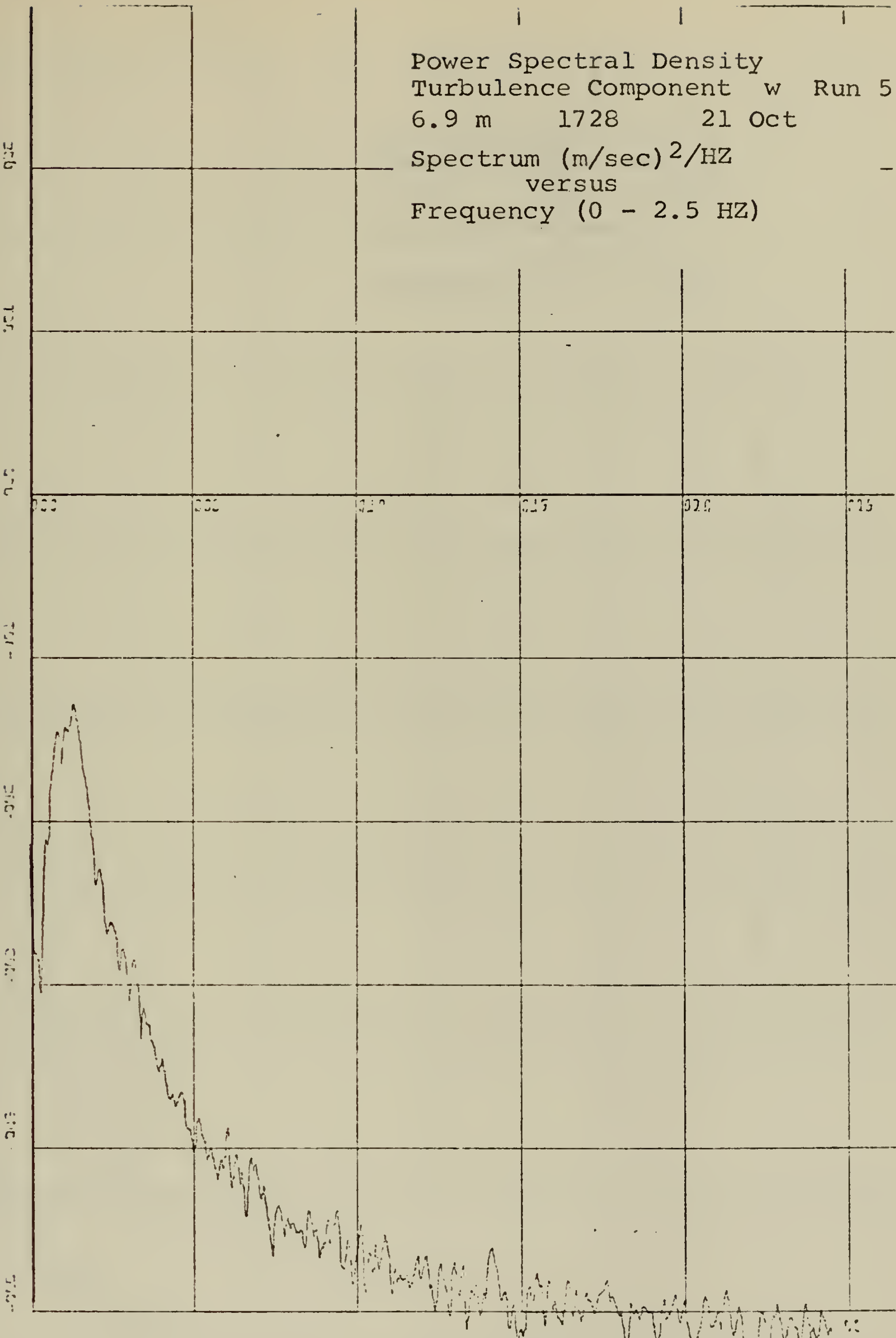

Power Spectral Density
Turbulence Component w Run 5
6.9 m 1728 21 Oct
Spectrum (m/sec)^2/HZ
versus
Frequency (0 - 2.5 HZ)

Figure 43.

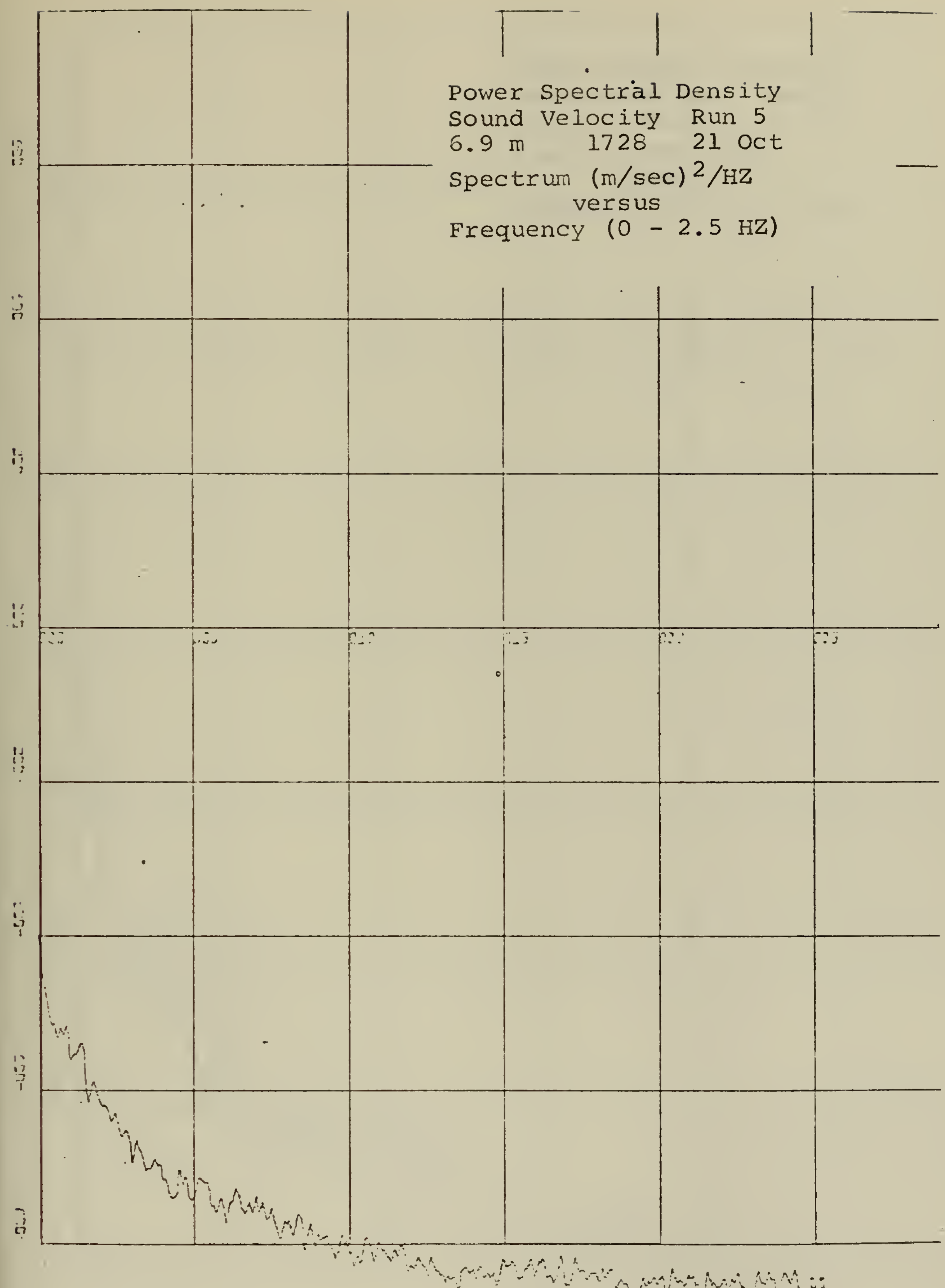

Power Spectral Density
Sound Velocity Run 5
6.9 m 1728 21 Oct
Spectrum (m/sec)2/HZ
versus
Frequency (0 - 2.5 HZ)

Figure 44.

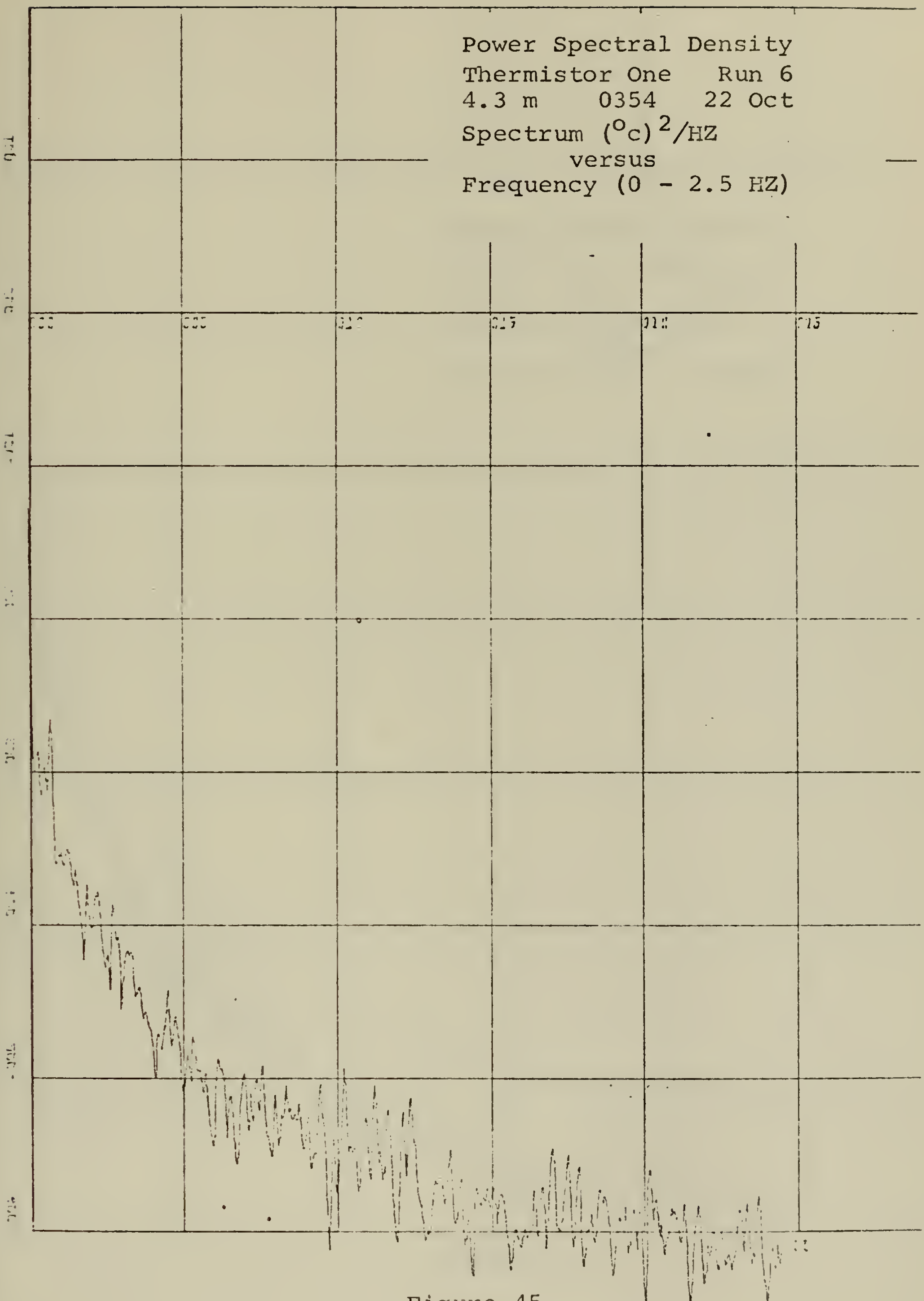

Power Spectral Density
Thermistor One Run 6
4.3 m 0354 22 Oct
Spectrum $(^{o}c)^{2}$/HZ
versus
Frequency (0 - 2.5 HZ)

Figure 45.

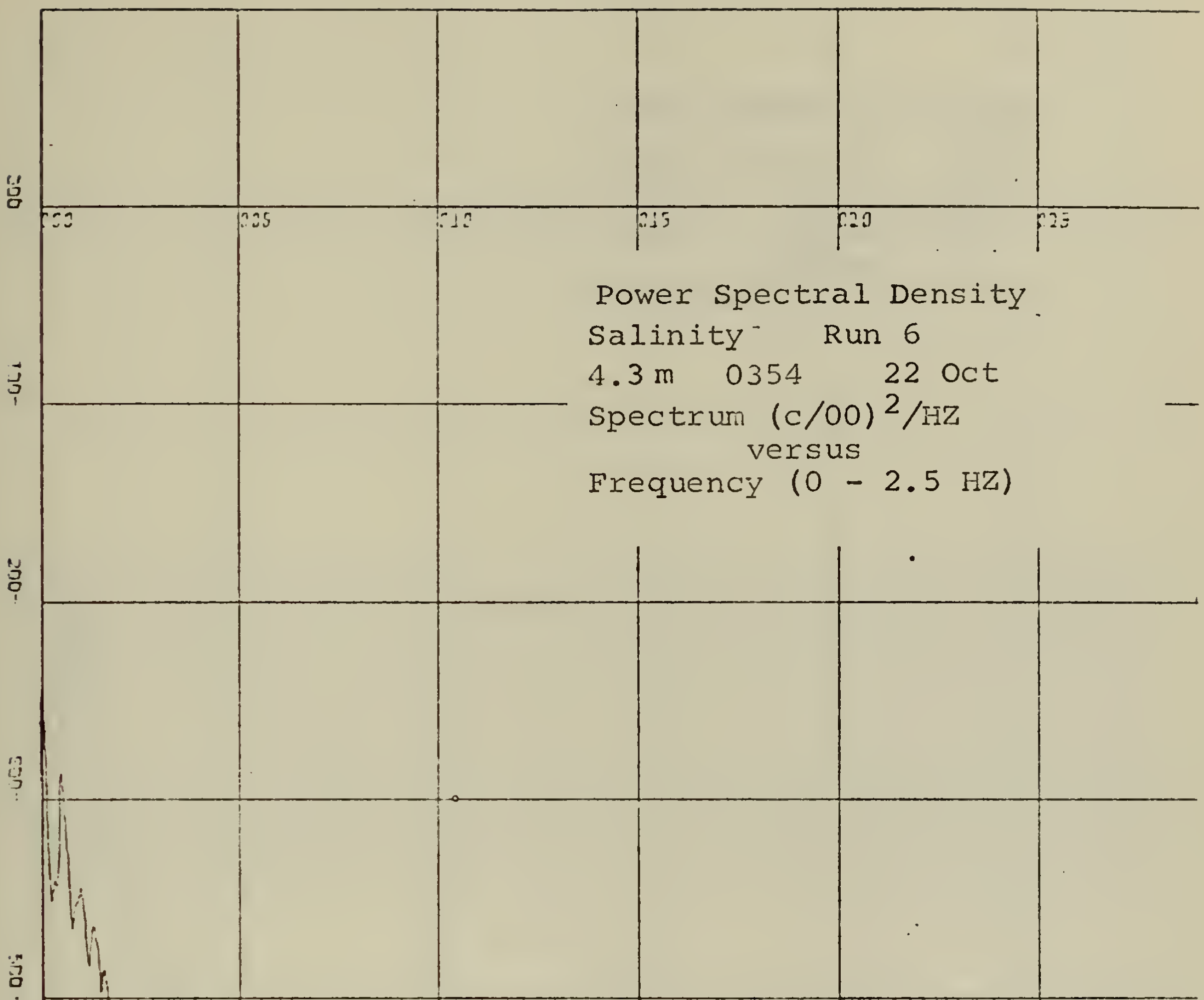

Power Spectral Density
Salinity Run 6
4.3 m 0354 22 Oct
Spectrum (c/00)^2/HZ
versus
Frequency (0 - 2.5 HZ)

Figure 46.

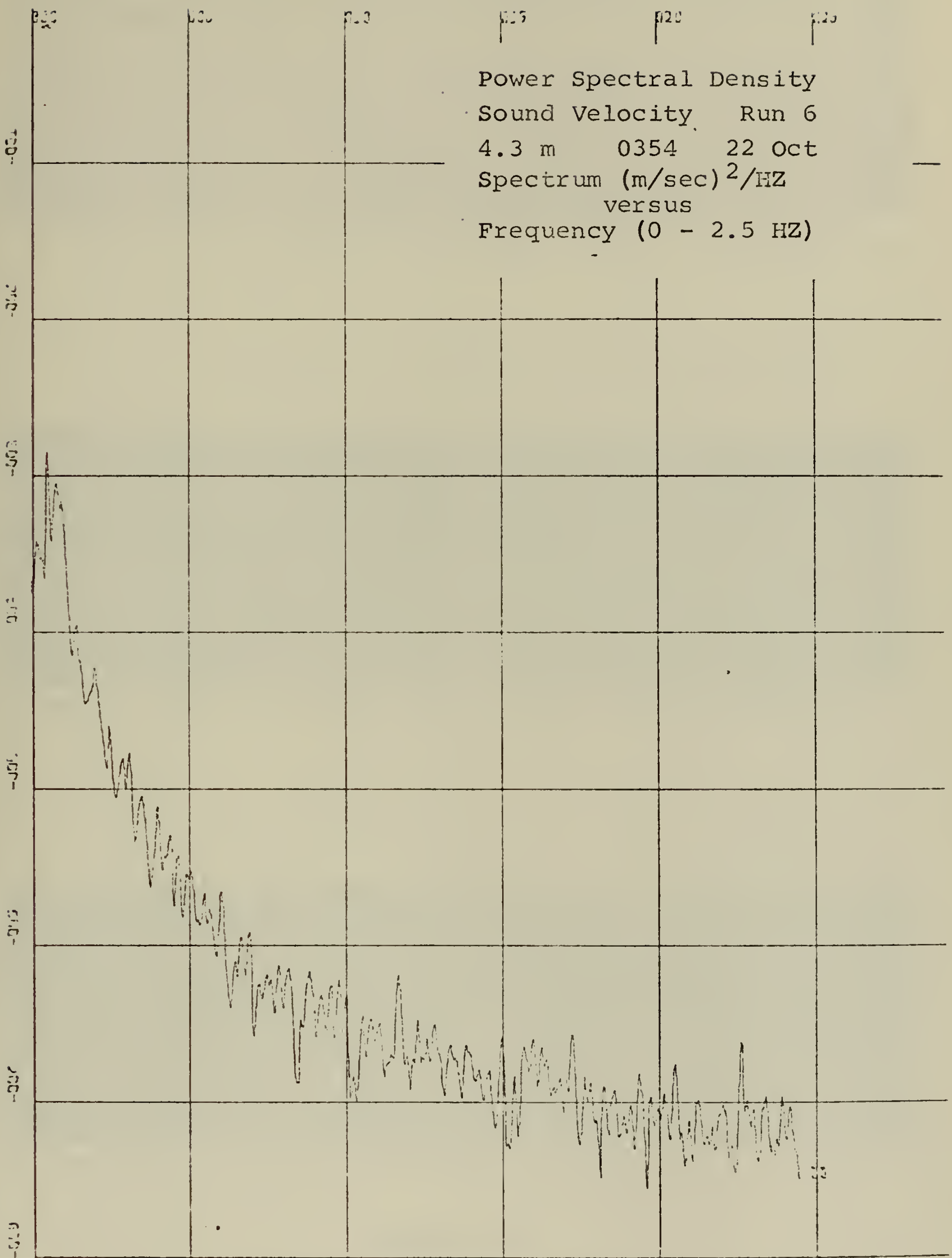

Power Spectral Density
Sound Velocity Run 6
4.3 m 0354 22 Oct
Spectrum $(m/sec)^2/HZ$
versus
Frequency (0 - 2.5 HZ)

Figure 47.

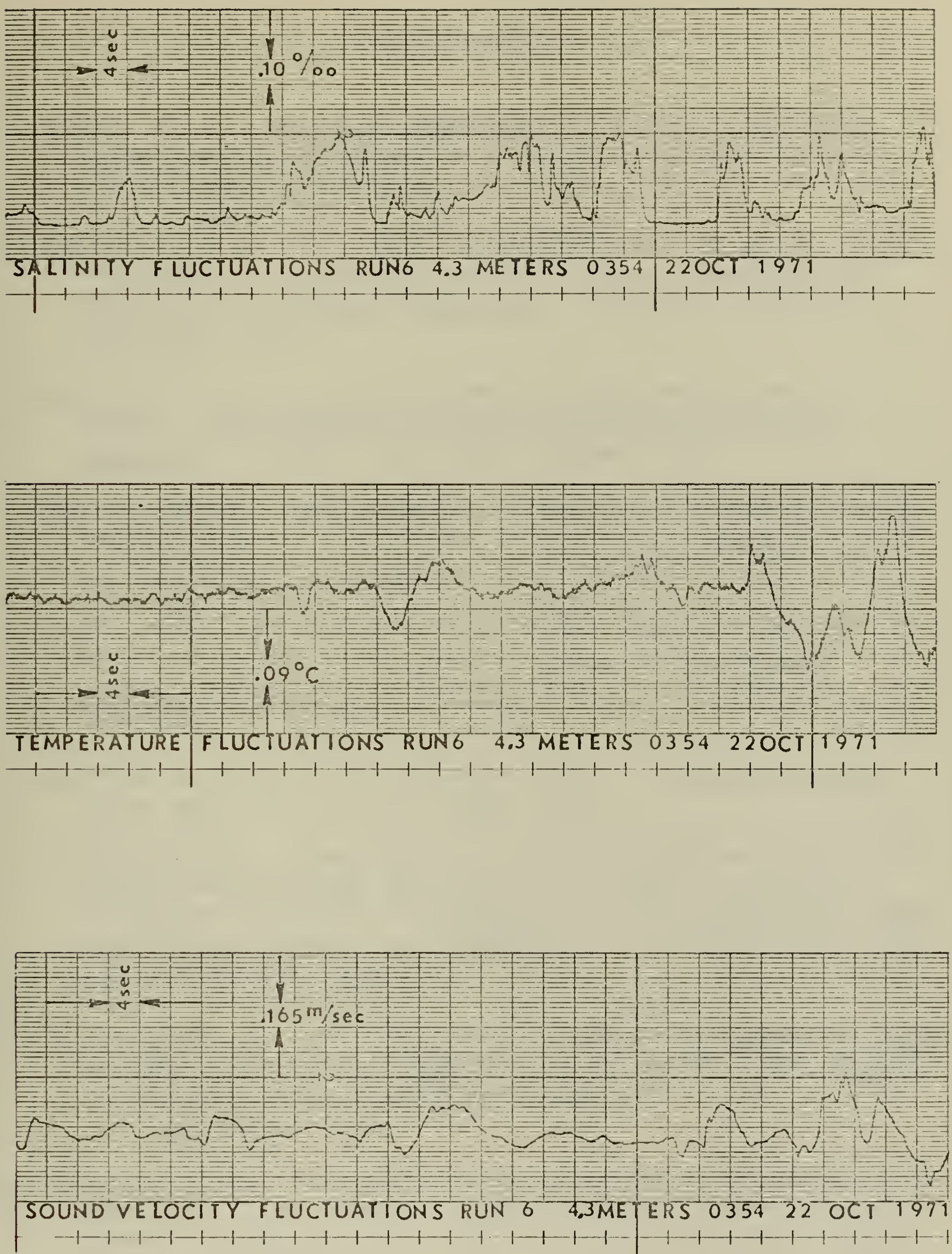


Figure 48.

Typical Brush Recording Trace.

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13. ABSTRACT

The temporal variations of salinity, temperature, water turbulence components, surface wave height, acoustic amplitude and acoustic velocity were studied statistically by computing the auto-correlations and power spectral densities. Correlation times were high for temperature fluctuations with a decay time (e^{-1}) being of the order of forty seconds or greater for temperature and of the order of two seconds for the other parameters. All parameters were shown to exhibit maximum energy at the periods of the predominant surface wave energy.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Sound Velocity						
Temperature						
Salinity						
Wave Turbulence						
Acoustic Phase						
Acoustic Amplitude						

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